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Final Report
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Assessment and Guide for Meeting Dissolved Oxygen Water Quality Standards for Hydroelectric Plant Discharges

Prepared by
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Wellsboro, Pennsylvania

REPORT SUMMARY

SUBJECTS: Hydroelectric / Land and water quality—chemistry and physics

TOPICS: Dissolved oxygen; Water quality; Licensing; Fish protection; Regulatory agencies; Hydroelectric power

AUDIENCE: Biologists and environmental engineers / Generation managers

Assessment and Guide for Meeting Dissolved Oxygen Water Quality Standards for Hydroelectric Plant Discharges

To meet relicensing requirements, hydro discharges must maintain adequate dissolved oxygen to maintain aquatic life. This guide identifies and assesses the techniques that can enhance dissolved oxygen levels and enables utilities to understand and comply cost-effectively with the applicable water quality standards.

BACKGROUND

Several hundred hydro plants in the United States will need relicensing in the 1990s and will have to meet the requirements of the Electric Consumers Protection Act of 1986. In particular, hydro discharges must comply with applicable water quality standards for dissolved oxygen. Much research has been conducted on aeration, particularly in the southeastern United States, but this information has never been assembled in a usable guide.

OBJECTIVE

To provide a technology assessment and step-by-step guide addressing the site-specific issue of the dissolved oxygen level of a hydroelectric plant discharge, particularly regarding relicensing.

APPROACH

Investigators assembled and synthesized information from utilities and regulatory agencies on the identification, monitoring, biological consequences, mitigation, and regulation of dissolved oxygen water quality problems. An industry peer review group was involved throughout the work.

RESULTS

This publication is a step-by-step guide that may be followed in addressing hydroelectric water quality issues. It covers the identification of applicable water quality standards, data compilation, testing for compliance, and possible mitigation measures; it also includes a discussion of the biological effects of low dissolved oxygen levels.

The investigators identified several techniques that can increase dissolved oxygen levels from 2 to 4+ mg/L, depending on site-specific constraints. Techniques discussed include forebay O_2 injection, weirs, turbine venting,

epilimnion surface water pumps, selective withdrawal, reservoir aeration, and combination approaches. Each approach has its own characteristics:

- Turbine venting is often low in capital cost but may result in significant efficiency reductions (lost power revenue).
- Epilimnion surface water pumps are easy to install and do not affect generating equipment. They are most effective in areas in which there are large differences between dissolved oxygen available in epilimnion and dissolved oxygen in normal release.
- When lost power revenues and water temperature are of high priority, pure oxygen injection in the forebay becomes economically attractive, especially when the head is greater than 60 ft, because of good oxygen transfer efficiency.
- A combination of techniques is often the most attractive approach.

EPRI PERSPECTIVE

This assessment and guide should help utilities make cost-effective, site-specific decisions for affected hydro projects. The methods presented provide an approach for screening and eliminating mitigation techniques not appropriate for a given site. Although the guide reports much experience on techniques such as turbine or draft tube venting and reservoir aerations, there are numerous site-specific variables that make exact prediction of performance difficult. Field testing may be required for some techniques to reduce uncertainty and risk.

PROJECT

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Research Project 2694-8

Final Report, November 1990

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ABSTRACT

An EPRI guidebook has been prepared to assist hydroelectric utilities when addressing state water quality dissolved oxygen standards. Although the material is particularly suited to utilities that are either currently involved in a re-licensing application or are preparing for one, it may also be applied to new license applications. The manual presents a recommended step-by-step Guide that may be followed throughout the entire process. The procedure stresses agency involvement, and emphasizes the need for a detailed definition of the imposed standard. The Guide continues with information regarding monitoring system requirements, data collection procedures, considerations for site-specific standards, compliance determination, and selection of an efficient aeration system. The Guide is referenced to a wealth of background information located in subsequent sections. Topics covered by the reference material include a description of the water quality mechanisms that lead to low DO levels, agency considerations, biological effects, aeration techniques, and monitoring systems. The appendices contain a state-by-state listing of agency contacts, the results of recent TVA fisheries research, and additional material to estimate the size and cost of the various aeration techniques. Nearly 400 sources of dissolved oxygen information are referenced in the guidebook.

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EXECUTIVE SUMMARY

GUIDEBOOK OBJECTIVES

The objective of this manual is to provide a step-by-step Guide, accompanied by the technical resources and data, that a hydroelectric utility may employ when addressing the issue of dissolved oxygen levels in facility discharges, particularly as it applies to the relicensing process. Because the issue is site-specific in nature, the material is presented in a format that allows individual users to apply the procedures to their particular situation.

SUMMARY

The Guide (Section 2) is divided into four stages:

1) Identifying applicable water quality standards;
2) Compiling data;
3) Testing for compliance; and,
4) Evaluating mitigation measures.

The identification of applicable standards can be a difficult process because it involves more than simply locating the pertinent state water quality doctrine. The Guide strongly urges utilities to consult with the involved agencies early in the re-licensing process. Dissolved oxygen water quality standards are designated by each state for various water bodies, and are mostly influenced by the local fishery populations. Standards will prescribe various DO levels, depending primarily upon species and sometimes upon the various life-stages of these species. Thus, it is important for the facility to be assigned a well defined standard that not only includes the DO levels that are to be maintained, but also the basis of these levels. In the data-gathering process, an applicant may discover particular circumstances that may warrant a variance in the DO standard. For

example, the statewide standard may impose high DO levels for reproduction of a particular species of fish. If the downstream fishery is of a put-and-take nature, natural reproduction is insignificant and the facility may qualify for a site-specific standard. If the legal basis exists for site-specific standards, the applicant may choose to pursue them. Before such action is taken, however, a cost analysis should be made to determine if the effort is economically worthwhile.

Few water quality standards clearly define how the particular DO levels are to be measured. Usually, overall daily DO averages are imposed, accompanied by absolute minimum levels. However, both daily averages and minimum levels can be arrived at in any number of ways. The mathematical details of determining the imposed DO levels must also be defined early in the consultation process. In addition, acceptable data collection methods must be clearly defined, before an applicant begins a monitoring program. The definition should include location of measurement, technique or equipment used, frequency of measurement, and existing conditions. These criteria are important not only for new monitoring systems, but also for pre-existing data. To avoid problems, close coordination with the agencies is recommended.

When a facility is required to provide additional aeration, alternative techniques must be evaluated. The Guide provides an 8-step process that can be used to select a viable system. The 8-steps involve a process of elimination based upon various stages of technical viability, design, economics, environmental concerns, field testing, and an overall level of confidence.

A particularly fundamental parameter that must be established before a final aeration system is selected is the cost of lost power revenue. The value an applicant places upon cost of lost power plays a major role in determining which aeration technique is most economically viable, and must be decided early in the selection process.

Three of the more often considered techniques are turbine venting, epilimnion surface water pumps, and pure oxygen injection. Although

turbine venting is often low in capital cost, reduced turbine efficiency (i.e., lost power revenue) can be significant. Furthermore, due to inherent limitations and uncertainties in the technique, it is currently limited in application. Nevertheless, with further research and testing, self-venting turbines may eventually achieve significant DO increases at sites where runner replacements can be justified.

Epilimnion surface water pumps are appealing from an installation point of view. They do not directly affect generating equipment, but do require power to operate. Temperature effects, however, and high first-costs can eliminate the pumps from consideration.

When lost power revenues are of high priority, pure oxygen injection in the forebay becomes economically attractive. The technique is particularly applicable to reservoirs with moderate to high heads (60-feet or greater) because of good oxygen transfer efficiencies, a low first-cost, and the fact that the technique has no direct effect on power generation.

Because most hydroelectric facilities are operated as peak-power producers, a combination of aeration systems should be considered. For example, a tailwater aeration system may be used to increase the small, non-generating flows to a near-saturated DO level, and a secondary aeration system would be provided to aerate the generation flows. Because of the 24-hour DO-level averaging included in most standards, the second system would normally only be required to operate at a level sufficient to meet the minimum DO standard.

The process presented by the Guide (Section 2) is meant to be practical. Information is available in subsequent sections and the appendices for the applicant to: understand the basic concepts of reservoir water quality mechanisms resulting in low DO levels; grasp the goals of the agencies involved; perceive the fishery issues at stake; design a data monitoring system; and compare the various aeration techniques. Because the comparison of techniques involves a considerable amount of engineering, simplified, qualified rules-of-thumb have been provided. Finally, nearly 400 references have been used to compile the information, and are listed for the applicant's use.

Section 1

INTRODUCTION

PURPOSE AND OBJECTIVES

The 1990s will be a period of intense hydroelectric relicensing activity. Not only are there nearly 300 hydroelectric relicensing cases expected, but applicants now must comply with major legislative changes in hydroelectric licensing process as a result of the Electric Consumers Protection Act of 1986 (ECPA). ECPA amended the criteria for relicensing decisions, modified the contents required in relicensing applications, and revised application filing procedures. EPRI Guide AP-6038 outlines detailed steps applicants can follow in implementing an effective relicensing strategy.

Passage of ECPA also impacted the way licensing issues concerning fisheries and environmental quality concerns are treated. Equal consideration must now be given to energy production, conservation, recreation, protection of fish and wildlife, and the preservation of the environment. In that regard, applicants now need to meet dissolved oxygen water quality requirements as part of the licensing or relicensing process. These requirements are generally based upon individual state water quality standards, but will also be influenced by additional agencies such as the U.S. Fish & Wildlife Service[1].

Because dissolved oxygen is a relatively new hydropower relicensing concern, many owners may not fully recognize the issues, complexity, costs, and available options. As part of its overall effort to aid owners in the relicensing process, EPRI has undertaken the task of reviewing and compiling the available information concerning all

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[1]Even though a facility's dissolved oxygen standard may be the result of influences from organizations other than state water quality agencies, for ease of discussion in this manual, the imposed standard shall be termed the "state standard".

aspects of dissolved oxygen in the licensing process. The overall objective was to provide utilities with a step-by-step Guide that could be used when addressing dissolved oxygen (DO) concerns. The Guide is found in Section 2 of this manual.

Section 3, Description of the Problem, compiled from years of research conducted on reservoirs, describes the circumstances that contribute to low DO levels, and their downstream effects. This section summarizes available information from all over the United States and can help owner-operators understand how DO may vary at their projects. To develop a better understanding of the various agencies involved in the licensing process, Section 4, Agency Involvement, is included.

Realizing that practically all hydroelectric sites are different, and downstream users are just as varied, the manual considers the possibility of site-specific standards, both in the Guide, and through the information of Section 5, Fishery Considerations. Section 5 details the various biological effects that result from low dissolved oxygen discharges, and the implications these effects have with the agencies involved. If owners wish to pursue site-specific standards, a discussion has been provided for each region of the country that presents the pertinent fish species of concern, and the current findings of researchers examining the effects of various dissolved oxygen levels.

A major part of the dissolved oxygen issue is selecting an efficient aeration system, should one be required. Of the several dozen techniques experimented with in the past, only seven are considered particularly viable. The Guide presents an 8-step process to select the best technique for a particular site. The process is based upon the imposed DO standard; the oxygen requirement at a particular site; the costs associated with installation, operation, maintenance, and energy; and the level of confidence associated with the technique. To detail the procedure and highlight the various facets of each system, Section 6, Techniques for Improving Dissolved Oxygen Levels, is provided. The section discusses ten different applications of the seven viable techniques. Each of the ten applications addresses the following areas:

- Physical Aspects
- Working Principles
- Limitations, Constraints, and Trade-offs
- Major Obstacles to Installation
- Environmental Effects
- Equipment Life Expectancy
- Safety
- Possible Modes of Failure
- Level of Confidence
- Sizing
- Costs
- Case Studies

Often, however, the best technique is not a single aeration system, but a combination of systems, each operating under its optimum conditions. Section 6 considers four potentially attractive combinations.

Finally, three new developments that hold promise are discussed. All three of the approaches are based upon side-stream injection techniques, and are applicable to both large storage reservoirs and run-of-river facilities.

One of the more frequent problems encountered in dealing with the issue of dissolved oxygen is a lack of background data. Today's licenses require monitoring systems be installed, and existing conditions recorded. Section 7, Dissolved Oxygen Monitoring and Modeling, considers the major aspects of monitoring, including typical license requirements, objectives in monitoring, available monitoring systems, and experiences of users.

Finally, the Appendices support the earlier sections with additional information regarding reservoir and tailwater water quality, related fishery experiments, the licensing action regarding the Upper Ohio River Basin, details of cost analysis for system comparisons, and a special section dealing with the various aspects of air and pure oxygen. Also included is a state-by-state contact list of agencies likely to be involved in DO licensing issues.

HOW TO USE THIS REPORT

The underlying concern in assembling the material for this manual was that it be practical. The Guide (Section 2) was written to ease the process of coming to grips with a new problem. The information is presented in an effort to minimize problems that may occur when issues (and end points) are not clearly defined upfront.

Because the issue of dissolved oxygen is extremely site-specific, the subjects of monitoring and aeration system selection have been presented with many examples. The sizing and cost examples presented in Section 6 are meant to be mimicked using the values specific to each user's site. Keeping the practical aspect in mind, none of the examples have been held to close tolerances of error. The purpose is to compare aeration techniques and select the most viable alternative. Once selected, it is recommended that the owner seek out professional engineering talent to provide the final design.

For someone new to the subject of dissolved oxygen and its relationship to hydropower discharges, Section 2 (the Guide) is the suggested starting point. Be forewarned, however, that if the Guide is followed religiously, no page of the remaining five sections will remain unturned.

More experienced users may wish to consult only the section dealing with a particular aspect of the problem. For example, those considering site-specific standards may only consider the biological information presented in Section 5. Section 6 can be used by those well into the licensing process, seeking clarification and understanding of the myriad of aeration techniques.

As a final word, dissolved oxygen in hydroelectric discharges remains a complicated and site-specific issue. None of the aeration techniques are guaranteed to work. In fact, very few have.....the first time around.

Section 2

GUIDE FOR MEETING DISSOLVED OXYGEN WATER QUALITY STANDARDS

Because of the Electric Consumers Protection Act of 1986 (ECPA), the licensing process for hydroelectric facilities now gives equal consideration to energy production and the preservation of the environment. Under ECPA, applicants are required to meet water quality standards which include levels for dissolved oxygen. The following Guide has been developed to aid hydroelectric owners that are either currently addressing, or those that will soon be addressing, dissolved oxygen issues.

The Guide encourages agency participation throughout the process[1], but particularly emphasizes the need for contact early-on and the establishment of well defined dissolved oxygen standards. The definition should establish the levels that must be attained, the rationale for such levels, and the exact procedures that are to be used in determining if the levels exist. Based upon the detailed definition, the owner can efficiently gather water quality data to determine what measures, if any, are required to meet the standards. In the process, the applicant may also discover potential for reduced, site-specific standards, but this will only be possible if the original definition includes the rationale for the standard.

As illustrated in Figure 2-1, the Guide can be divided into four basic stages:

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[1]When licensing is involved, the responsibility for consultation with agencies is clearly spelled out in FERC requirements. Section 4.1 discusses FERC and other agency regulations, supported by court decisions, that clearly establish the need for maintenance of dissolved oxygen concentrations in compliance with state water quality regulations and standards.

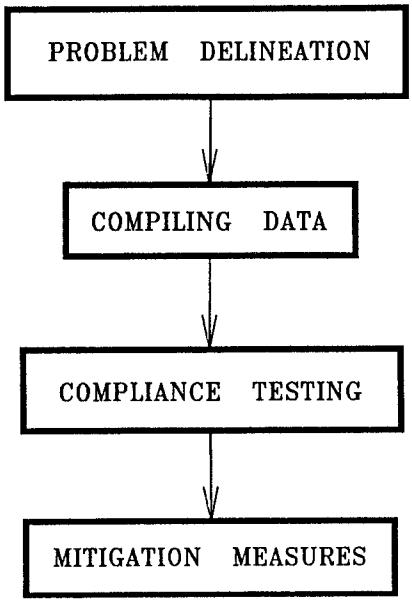


Figure 2-1. Four-Step Process to Meeting DO Requirements.

1) Problem Delineation: Identification of Applicable Water Quality Standards
2) Compiling Data
3) Testing For Compliance
4) Mitigation Measures

2.1 PROBLEM DELINEATION: IDENTIFICATION OF APPLICABLE WATER QUALITY STANDARDS

The subject of dissolved oxygen (DO) levels in reservoir discharges is an extremely involved one. It not only encompasses the fields of environmental chemistry, engineering, biology, physics, and law, but it can also become a major cost item in the budget of some facilities. Owners should make a diligent effort to understand the subject as thoroughly as possible.

Predicting DO Discharge Levels

The dissolved oxygen level in reservoir discharges can be considered the result of three influences: inflow factors, reservoir processes, and outflow (operational) factors. Typically, pertinent inflow characteristics include:

- Temperature characteristics
- Chemical composition of the water
- Flow characteristics (seasonal, annual, storms)
- Incoming dissolved oxygen level
- Watershed characteristics
- Upstream reservoirs

Reservoir processes can be extremely complex and interrelated. They normally include:

- Thermal stratification
- Various chemical and biological oxygen demanding processes
- Retention time
- Age of reservoir
- Pool level management policy
- Hydrometeorological effects

Outlet factors include:

- Depth of outlet
- Turbine characteristics
- Relative release rate, duration
- Peaking versus continuous generation
- Leakage

Thus, because of the complex interaction of the above factors, predicting whether discharges meet water quality standards is extremely difficult. Complex state-of-the-art reservoir models (refer to Section 7.7) can provide accurate predictions, but are relatively expensive and intensive efforts. In a general sense, however, reservoirs with the following conditions are more likely to encounter periods when the discharge contains less than 5 mg/L DO:

Depth at dam:	> 50-feet
Power capacity:	> 10 MW
Reservoir volume:	> 50,000 acre-feet
Densimetric Froude Number:	< 7
Retention Time:	> 10-days

The Densimetric Froude Number is defined as:

$$F_d = \frac{0.01952\ L\ Q\ (V_1 - V_A)}{V_A^2} \times 10^3$$

where:

L = Reservoir length (miles)
Q = Average annual inflow (CFS)
V_A = Average annual volume (1,000 CFS-days)
V_1 = 1-foot above average storage (1,000 CFS-days)

Complexity of Water Quality Standards

In addition to the multitude of factors that control DO, to further complicate the situation, water quality standards are not always straightforward. Standards are sometimes linked to variables such as time of year, water temperature, designated uses of the water resource, fish species, and particular life stages of fish development.

For example, depending upon the classification of the river, the imposed standard may require dissolved oxygen levels downstream of the dam to average 5.0 mg/L or greater, and never go below 3.0 mg/L. There are, however, several methods for calculating the DO levels at a facility. The daily average value could be the result of:

1) a single daily reading;
2) the average of a morning reading and one taken in the evening;
3) the average of hourly readings taken 24-hours/day;
4) the average of hourly readings only taken during periods of generation; or,
5) the average of the single highest and single lowest reading taken over the 24-hour day.

The 3.0 mg/L minimum value could be interpreted as an "instantaneous" minimum, an hourly average, or a daily average. Because a generic procedure for determining the "average" and "minimum" values has not

been established, the definition of the standard must clearly spell out how values are to be measured and calculated.[2]

More complicated standards can impose 30-day means, 7-day means, and 7-day mean minimums. If a particular species of fish spawns downstream of the dam, the standard may include provisions for higher DO levels during the period of year when early life stages are present. Likewise, because fish health is not only dependent on DO levels, but also on temperature, the discharge DO standard may also be dictated by water temperature. Higher DO levels may be required if a certain temperature threshold is reached. Table 2-1 presents the dissolved oxygen water quality criteria recommended by the U.S. Environmental Protection Agency (USEPA) (Ref. 2-1). The table is more fully discussed in Sections 4 and 5.

Thus, because of the interaction of numerous factors that determine discharge DO levels, and the complexity of standards, extra effort must be put forth so that the proper water quality standards have been identified, and the rationale for applying them to a particular site is well understood. Consultation with the agencies that develop, update, and apply the water quality standards is one of the best assurances that time and effort will not be wasted. In addition, working with agencies early-on offers other advantages:

Early contact demonstrates a willingness on the part of the utility to address the problem.

Early contact establishes an atmosphere of collaboration and cooperation.

The applicant is more likely to learn of recent or pending changes in water quality standards (refer to Section 4.2 for current trends and conflicts with agency regulations);

Cooperation will provide the best atmosphere for problem resolution. As such, the chance for success when seeking site-specific standards are increased.

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[2]With the advent of personal computers, continuous monitoring is becoming relatively inexpensive, and a generic procedure may evolve once the equipment is accepted by the industry.

Table 2-1

WATER QUALITY CRITERIA FOR AMBIENT DISSOLVED OXYGEN CONCENTRATION

	Coldwater Criteria		Warmwater Criteria	
	Early Life Stages[1,2]	Other Life Stages	Early Life Stages[2]	Other Life Stages
30-Day Mean	NA[3]	6.5	NA	5.5
7-Day Mean	9.5 (6.5)	NA	6.0	NA
7-Day Mean Minimum	NA	5.0	NA	4.0
1-Day Minimum[4,5]	8.0 (5.0)	4.0	5.0	3.0

1. These are water column concentrations recommended to achieve the required intergravel dissolved oxygen concentrations shown in parentheses. The 3 mg/L differential is discussed in the criteria document. For species that have early life stages exposed directly to the water column, the figures in parentheses apply.

2. Includes all embryonic and larval stages and all juvenile forms to 30-days following hatching.

3. NA (Not Applicable)

4. For highly manipulative discharges, further restrictions apply.

5. All minima should be considered as instantaneous concentrations to be achieved at all times.

(Ref. 2-1)

Applicants may refer to Appendix A, Agency Contact List, as a starting point to identify agencies. Additional organizations may be discovered by reviewing other facilities' licenses within the same river basin or general vicinity, or through discussions with the listed agency contacts.

Before agency consultation is initiated, however, it is recommended that applicants review Sections 3, 4, and 5. Section 3 provides further discussion on the factors that lead to low dissolved oxygen levels, and the effect when water low in DO is discharged. Section 4 deals with agency concerns and is presented to help applicants gain insight into the agency position on this issue and the goals they are working to achieve. Finally, Section 5 deals exclusively with the fishery aspect of low DO levels. The material can serve as a starting point to understand in detail the reasoning behind standards, and perhaps identify if site-specific standards are warranted.

Problem Delineation

The foremost objective of initial agency consultation should be to develop a detailed delineation of the problem (Figure 2-2). Delineation of the problem is the most critical element, and often the most debated issue in the entire process of meeting water quality standards. Problem delineation should begin with a reconnaissance study to identify as many of the site-specific factors as possible that affect, or are affected by, DO discharge levels. Next, precise DO levels should be established, accompanied by the conditions under which they apply. The rationale used to establish the specific DO levels should be clearly spelled out, including specific fish species and life stages of concern. Finally, details for compliance should be included.

Site Reconnaissance. Because water quality standards can vary with the reservoir, river, stream reach, and with existing or desired water uses, site-specific factors must be considered in defining the rationale behind dissolved oxygen standards. A reconnaissance of the waterway downstream from the project is essential in determining site-specific factors, because frequently, low DO is only one of many factors affecting water uses. Fisheries and other desirable water-uses may be potentially improved by increases in DO levels. However,

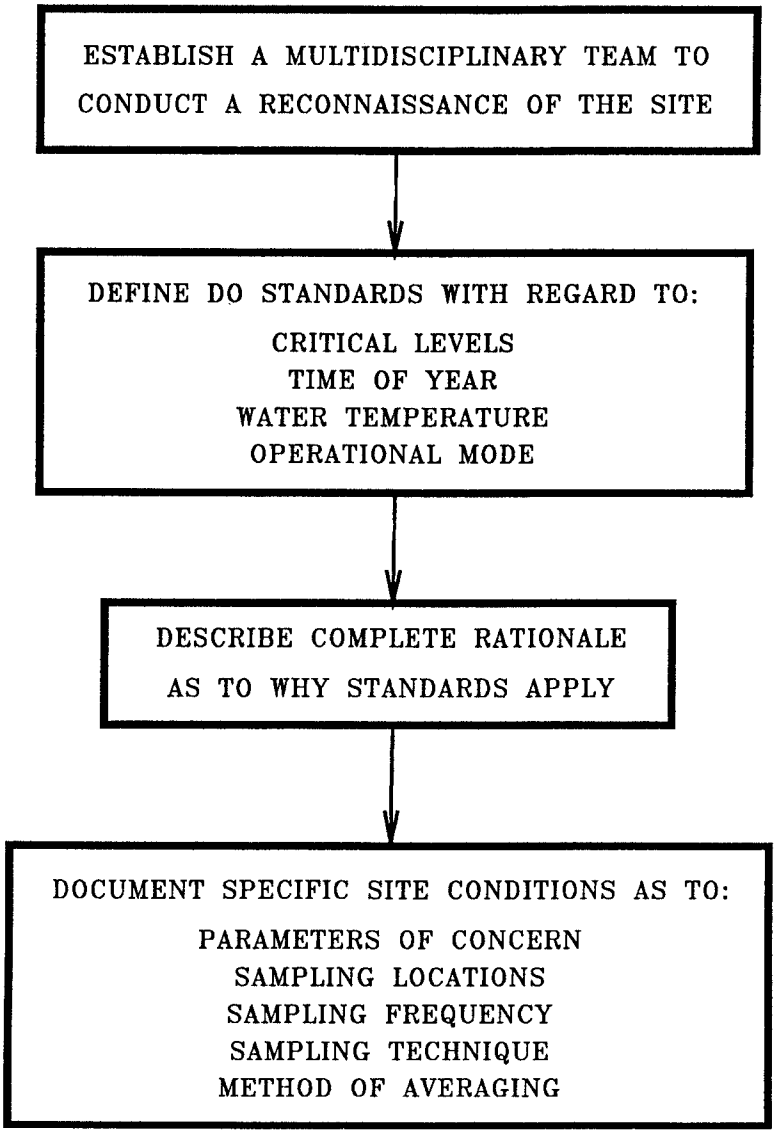


Figure 2-2. Problem Delineation

after a certain amount of water quality improvement is obtained, improvement in other factors (e.g., temperature, flow fluctuations, access, adjacent land use, channel characteristics, etc.) can be much more significant than further DO enhancement.

To be most effective, the reconnaissance should be undertaken by a multidisciplinary and multiagency team so that all viewpoints are represented. Also, such a survey should combine land, water, and possibly aerial views of the river and surrounding lands to identify factors potentially affecting the aquatic resources. Recent project experience has shown that aerial reconnaissance with agency personnel may identify other factors, unrelated to the initial concern, that are controlling downstream resources.

Defining the Standards. Once the reconnaissance survey has been performed, precise DO standards should be established. Critical levels should be spelled out in detail. If DO levels are linked to factors such as time of year, water temperature, or operational mode, the specific conditions under which they apply should be detailed.

Rationale Behind the Standards. A detailed rationale as to why the specific levels are applied should be included in the Problem Delineation. Fish species and their life stages of concern should be listed, as well as the fishery management goals and practices of the resource agencies. A detailed rationale will help the owner provide remedial measures in the most efficient manner, and perhaps, open the matter to consideration of site-specific standards.

Details of Applying the Standards. Finally, the Problem Delineation should define exactly how the standards are to be applied at the applicant's particular site. Points that should be included are: 1) a list of parameters to be monitored (see Section 7); 2) a detailed specification of acceptable data (exact locations of where DO data is to be collected, frequency of sampling, and acceptable techniques/-equipment used for sampling); and, 3) clear definitions of "averaging" for data analysis.

Parameters To Be Measured. Parameters to be measured can vary, depending on the objective of the monitoring system

and the required data. Problem delineation most likely established that downstream DO, flow, and temperature should be measured for basic compliance. However, if aeration systems are likely to result from the monitoring and data analysis, dissolved nitrogen levels should also be considered, along with the variability for each of the original parameters, particularly incoming DO. If DO is already known to be depleted at certain times, monitoring for hydrogen sulfide, iron, and manganese should be considered. This information will provide a complete foundation upon which the various aeration techniques can be compared.

If site-specific standards are a consideration, downstream surveys should be made. These surveys should include biological, industrial, municipal, and recreational uses of the discharge. Refer to Section 5 for further discussion as to the implications of these surveys, and various tolerance levels of specific fish species.

If the applicant suspects upstream influences are also degrading reservoir water quality, then reservoir inflows should be monitored. If inflow water quality worsens, low DO is likely to occur over a longer period each year, requiring additional aeration. These changes should be documented. Refer to Section 7.6 for further discussion concerning additional parameters for monitoring consideration.

Monitoring Site Selection. Sampling sites for compliance should be included in the problem delineation, and typically will include the scroll case and the tailrace. However, the applicant may wish to monitor additional sites to gain information pertinent to aeration system design and/or for use in pursuing site-specific standards. Additional monitoring site locations are especially useful if downstream conditions are not well defined. Agencies should be consulted to provide input into the site selection process, and should give formal approval of the final number and location of sites. Section 7.3 offers further discussion concerning

site selection. Guidance for selecting sites is illustrated in Table 2-2, and further discussion can be found in Section 7.

Table 2-2

MONITORING SITE SELECTION CONSIDERATIONS

Site Selection Based Upon:

- License terms
- Overall goals of monitoring, including:
  - Evaluation of aeration techniques
  - Determination of downstream do recovery
- The number of sites to be monitored
- Upstream conditions, including:
  - Reservoir inflows
  - Reservoir forebay
  - Reservoir outflows
- Downstream conditions, including:
  - Generation flows
  - Leakage flows
  - Spilled flows
  - Bypassed flows
  - Downstream reach characteristics

Site characteristics that determine difficulty of measurement include:

- Depth
- Turbulence
- Distance from powerhouse
- Turbidity
- Access
- Local inflows/wastewater discharges
- Special concerns (e.g., Spawning areas)

Frequency of Measurement. As with site-selection, frequency of monitoring for compliance should also be defined in the Problem Delineation. The frequency of measurement, however, is also dependent upon the monitoring objectives. For compliance testing, the frequency probably will be seasonally regulated. During the non-stratified portion of the year, DO and temperature can be measured weekly or monthly. During periods when DO is expected to be low, the discharge will need to be measured hourly, unless existing data indicate otherwise. More frequent monitoring is recommended if site-specific standards or aeration equipment is being considered. With the adaptation of personal computers, continuous monitoring has become more common, although problems with sensor fouling and vandalism continue to plague owners. Refer to Section 7.4 for more specific suggestions regarding the frequency of measurements for different situations.

Equipment Selection. Selection of monitoring system equipment should not be made hastily. FERC requirements may specify type of equipment and specific techniques that must be used for data gathering. Experiences of users of different systems and a partial list of available hardware can be found in Section 7.8 and Section 7.10.

2.2 COMPILING DATA

Determination of Data Needs

Once the problem has been delineated, the task at-hand is to determine if the facility is within compliance; this requires the compilation of data (Figure 2-3). However, before new monitoring programs are designed and implemented, existing data-sources should be examined (refer to Section 7.9). These sources include the facility's existing water quality records, government databases, previous licensing efforts for nearby hydro-facilities, and possibly, local watershed studies conducted by universities or other groups. The data from these sources, however, probably will not conform in all respects as to frequency of sampling, duration of sampling, tech-

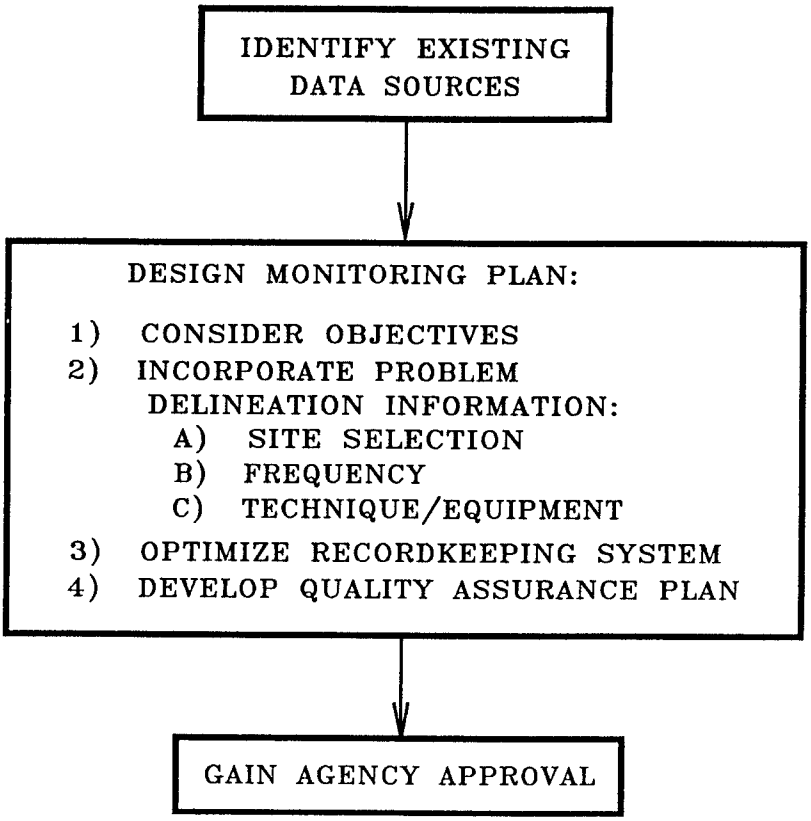


Figure 2-3. Compiling Data

niques used to gather and analyze the samples, and other requirements defined in the Problem Delineation. However, these data will be useful in designing the monitoring plan.

Designing a DO Monitoring Plan

In addition to the areas detailed in the Problem Delineation, thought should be given to the objectives of a monitoring system, storing the data in its most useable form, and incorporating a plan to assure that the data is accurate.

Defining Monitoring Objectives. If the problem has been delineated in cooperation with the agencies, this particular aspect has probably been pre-determined. However, the applicant should consider what the

ultimate result of the monitoring/compliance-determination effort could be (see Section 7.1). For example, if it is likely that aeration systems will be required in the future, it would be prudent to design and install a slightly more elaborate monitoring system that includes measurement of additional parameters. In this case, the monitoring system could also have the capability of recording aeration system performance following the implementation of an oxygen enhancement technique. If site-specific standards are a possibility, biological surveys should also be considered. If time and funding permit, applicants may wish to consider the advantages of modeling the affected area. Section 7.7 provides additional discussion concerning the various aspects of modeling.

Recordkeeping System. The monitoring design must include a record-keeping system. Again with future needs in mind, the recordkeeping system must be flexible enough to meet the basic initial require-ments, but also be capable of incorporation into a larger data analysis system. Section 7.5 presents the various levels of record-keeping systems, and examples of typical outputs.

Quality Assurance/Control Procedure. Although much effort has been put forth in developing DO monitoring equipment, reliable equipment requiring minimal maintenance has yet to evolve. Thus, to assure accuracy of the data, a detailed program of equipment calibration and maintenance should be established and rigidly followed.

Agency Review

DO monitoring plans for meeting FERC license requirements are re-viewed by governing state and federal resource agencies. Further-more, the agencies' comments must be submitted and addressed with the plan. For owners acting prior to licensing action and independent of agency consultation, it is possible that data obtained with unap-proved monitoring systems could be questioned at a later date. Section 7.2 provides examples of the FERC-approved monitoring plans with the typical requirements itemized.

The monitoring plan is implemented after it has been reviewed by the agencies and approved by FERC. If difficulties are encountered, the

agencies should be informed, and any modifications to the plan should be approved.

2.3 TESTING FOR COMPLIANCE

Using the database and the analysis procedures established in the Problem Delineation, testing for compliance (Figure 2-4) should be straightforward, and conclusions of all parties should concur. However, if the imposed standards were not clearly defined, and particularly, if the procedure for determining DO levels was not concisely presented, determining compliance could potentially become a contested matter. To reiterate, the definition of the standard must clearly detail how the DO values are to be determined.

If it is agreed that a facility is in compliance, the monitoring program should not be totally abandoned. In fact, FERC probably will require monitoring for a period of time to verify continued compliance. Depending on the site-specific situation, it may also be prudent to continue monitoring reservoir inflow quality to detect upstream changes that could result in discharges not meeting the water quality standards.

If the facility is not in compliance with the standards, the owner may wish to examine the potential of more site-specific DO standards.

Determine if Site-Specific Standards are Warranted

Because state water quality standards are universally applied throughout the state, it is conceivable that certain site-specific factors may warrant a change in the required dissolved oxygen level of the facility discharge. Although site-specific reductions in state standards are rare, the economics of oxygenating the large-volume discharges typical of hydroelectric powerplants may warrant their consideration.

In addition to the site exhibiting traits that may warrant different DO standards, it is essential that a legal basis exist for seeking revised standards. This legal basis may be nothing more than a clause within the water quality standards that permits variations if

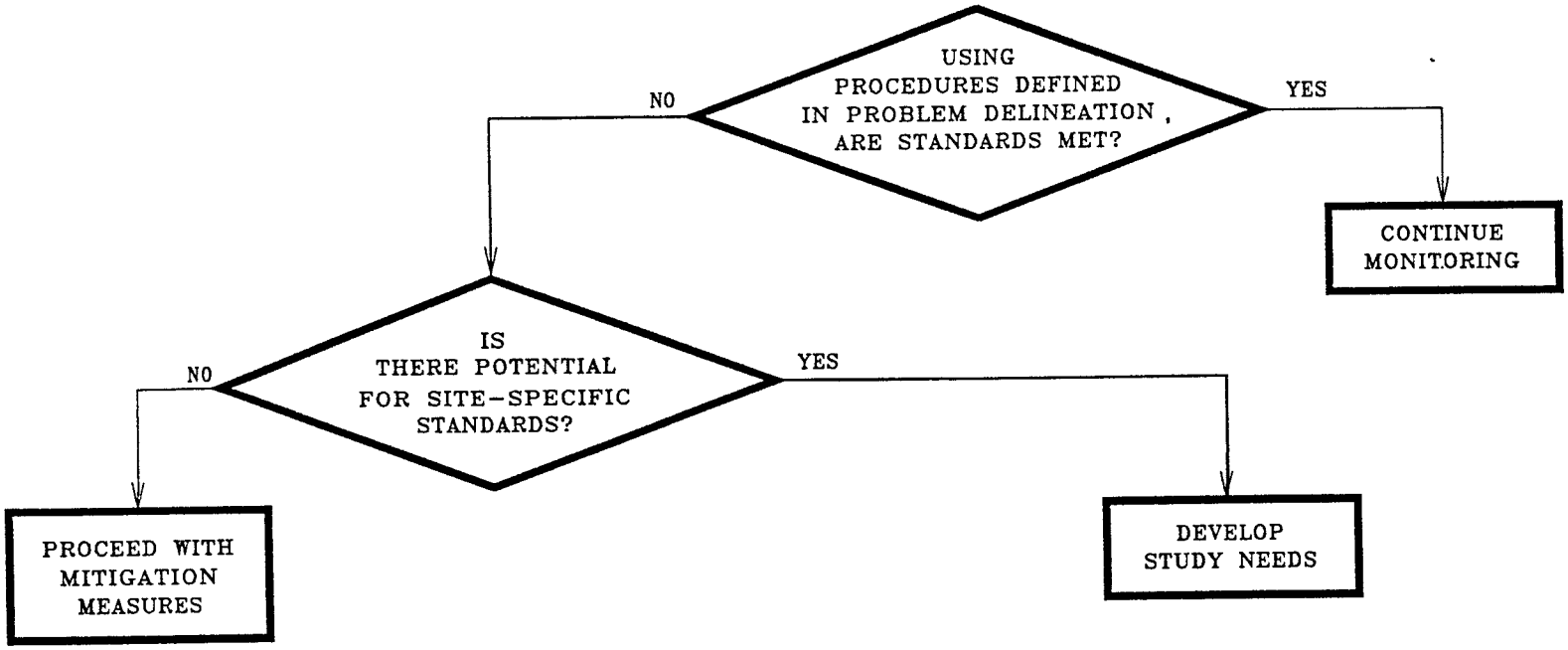


Figure 2-4. Testing for Compliance

extenuating circumstances apply. It would be rare that a legal doctrine, such as water quality standards, would be adopted without containing qualifications for its application. However, if a legal basis does not exist to procure site-specific standards, then none can be awarded.

Seeking site-specific standards can be time consuming and an expensive exercise. Before undertaking such an effort, the overall chances of success should be considered, including an assessment of the actual savings gained if lower DO discharge levels are allowed. Depending on the size of the project, the cost of obtaining site-specific standards can be more than the savings realized in their application.

Identification of Circumstances Warranting Site-Specific Standards. A multitude of factors enter into determining the downstream DO levels actually required from hydropower discharges. To warrant a reduction in water quality standards, the downstream situation must be clearly shown to be an exceptional case, where the criteria is determined by factors other than those from which the general standards were developed. An example would be a dam with a put-and-take downstream fishery, and general standards that include specific DO levels for spawning and early life stages of fish. It may be possible to obtain site-specific standards that apply only to adult fish.

One of the more promising approaches to considering site-specific DO levels is to provide fishery data that demonstrate insignificant impact by periodic releases of water containing slightly lower DO levels than general standards allow. Studies conducted at the site could show that the pulsing operation of the facility, particularly in peaking-powerplants, has very little effect on the fishery population. The pulsing operation could discharge water below state standards, yet be of short enough duration to not affect fish condition. Refer to Appendix D for pertinent work that TVA has done in this area.

Other factors affecting fish condition are availability of adequate food base and temperature; dissolved oxygen may play a secondary role. A facility may enhance DO levels through aeration equipment;

however, fish condition may remain poor due to a lack of sufficient food supply. Also, discharge temperatures may not support desirable fish species. It would be unreasonable to burden a facility with the expense of enhancing DO levels to meet a standard, when the desired goal of a healthy fish population cannot possibly be achieved due to other factors.

Site-specific standards may also be tied to issues other than fish condition. TVA experience has shown (Ref. 2-2 and 2-3) that the development of overall project tailwater management plans with a focus on downstream uses can be extremely beneficial to the hydropower plant owner/operator, as well as to downstream users. Focusing on various types of constraints to attaining the tailwater objective appears to be much more fruitful than simply providing numerical criteria at the point of release. If access to the tailwater is limited, expending large sums of money to enhance a fishery that cannot be enjoyed is difficult to justify. Similarly, if the tailwater demonstrates conditions that provide for rapid DO recovery from natural conditions in a short reach, the cost of enhancing DO immediately at the point of discharge may far exceed the total benefit attained in the short run of river benefitting from the enhancement.

Development of Study Needs. Potential options that could warrant site-specific standards should be defined and presented to the agencies for further input and approval. Once consensus has been reached on the potential of the options, it is then necessary to develop study needs and methodologies that will evaluate the options.

The goal of a study program is to obtain information that can be used in decision-making. If, after the data is gathered, there are differences regarding methodology, or key information was not obtained, the data collection effort may have been wasted. All aspects of the study need to be detailed, including the interpretation of the data. As with every other aspect of addressing DO standards, the governing agencies should be consulted for input and approval of the study needs and methodology.

Once the sampling and/or tests have been conducted in accordance with the agreed scope of work and methodology, site-specific standards and

management of downstream resources should be developed and evaluated for their impacts on all competing interests. Agency negotiations can then focus on the program that best meets the goals established by the National Environmental Policy Act (NEPA) and ECPA for "equal consideration" and optimum utilization of all resource values.

As discussed in Section 4.1, FERC now requires "equal consideration" be given to mitigation and enhancement of fish and wildlife, recreational opportunities, and the preservation of other aspects of environmental quality, as well as to hydroelectric power potential. Thus, negotiations with resource agencies regarding minimum DO concentrations should be maintained. Hydro project discharges should not be aimed at maximizing any single aspect, whether it be power production, fishery production, recreation, or some other goal. Rather, the resultant agreement should be a reasonable compromise that meets social, legal, biological, and economic goals and standards and exceeds minimal standards equitably for all competing interests. Such an agreement requires the willingness of all parties to compromise and consider all points of view rather than their own self-interest.

2.4 MITIGATION MEASURES

If the facility is found to be in non-compliance, the applicant must examine alternative mitigation measures. In spite of the work that has been accomplished over the last forty years, no single aeration technique can be designed and absolutely guaranteed to perform as predicted. Selection and design of an aeration system remains more of an art than an engineering science due to the large number of site-specific variables which interact in ways that are difficult, if not impossible, to predict. This makes forecasting system performance more of a best-estimate based upon the experience of others, rather than a calculated quantity with reasonable bounds of certainty. In recent years, however, engineers and researchers have added considerably to understanding the science involved in the systems. Their efforts can be attributed in most part to the increased activity of the regulatory agencies.

Determination of the Optimum Aeration Technique

The recommended procedure to select the optimum aeration system for a specific site uses both technical viability and total cost in an 8-step process of elimination. A discussion of each step, illustrated in Figure 2-5, follows.

1) Assess Site-Specific Technical Viability. In most cases, Table 2-3 will serve as a starting point to eliminate systems that are inappropriate based upon technical performance. Table 2-3 uses the magnitude of the DO deficit to segregate the techniques. The deficit is defined as:

DISSOLVED OXYGEN DEFICIT = SITE'S STANDARD - LOWEST ENTERING DO LEVEL

Table 2-3 is a very general representation, and should be applied with caution. Because the ability to transfer dissolved oxygen is dependent upon the difference between the saturation level of the discharge and the actual incoming DO level, Table 2-3 may not apply in all cases. When the DO concentration of the discharge approaches saturation, dissolving additional oxygen into the water becomes increasingly more

Table 2-3

TECHNICAL VIABILITY OF VARIOUS AERATION TECHNIQUES

MAXIMUM OXYGEN DEFICIT		
0 - 2 mg/L	2 - 4 mg/L	4+ mg/L
Operational Techniques	Operational Techniques	Operational Techniques
Forebay Oxygen Inject.	Forebay Oxygen Inject.	Forebay Oxygen Inject.
Weirs	Weirs	Weirs
Turbine Venting	Selective Withdrawal	Selective Withdrawal
Eplmn. Surf. Pumps*	Eplmn. Surf. Pumps*	Reservoir Aeration
	Combinations	Combinations

* - If temperature is not a factor

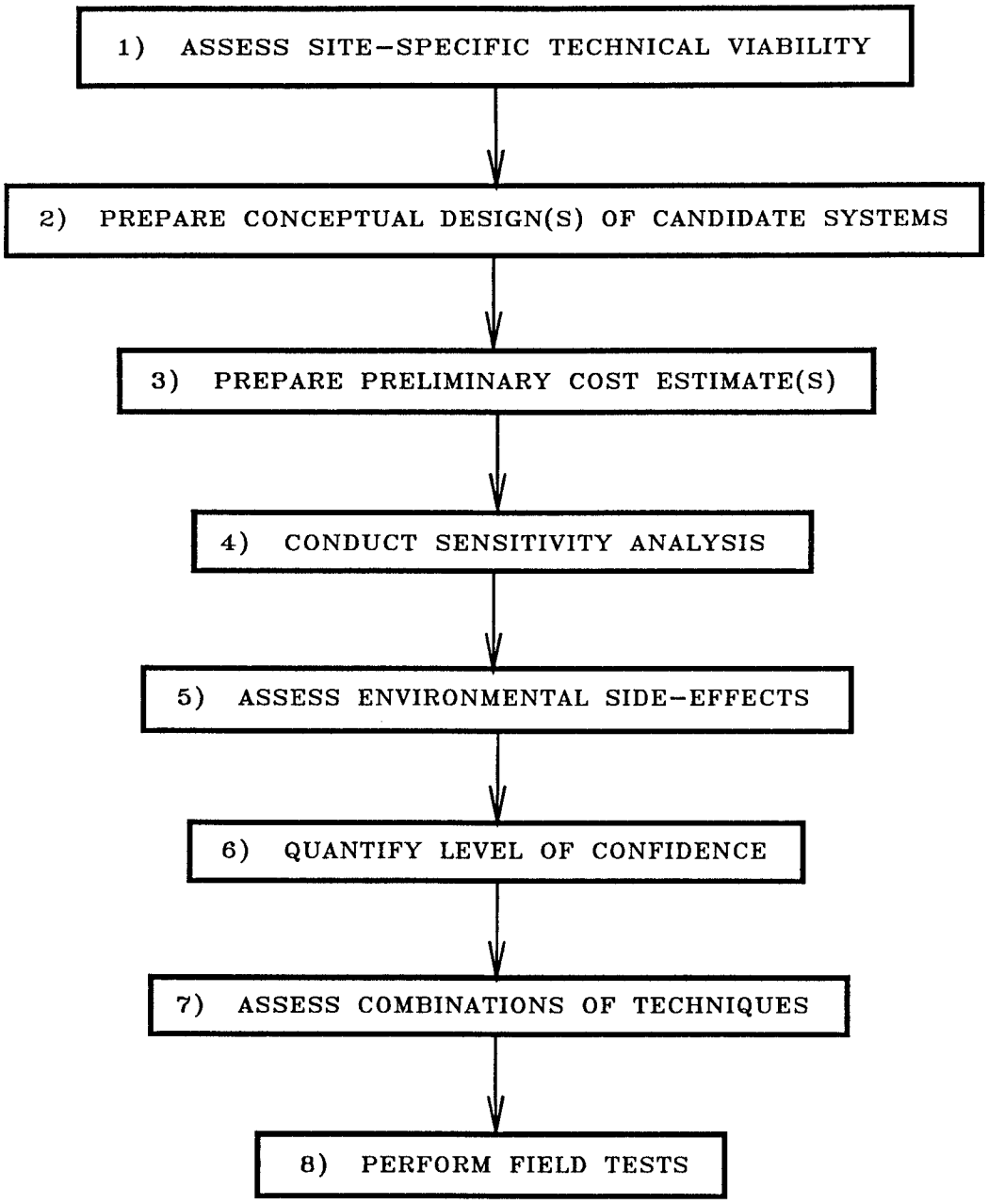


Figure 2-5. Process for Selection of Optimum Aeration Technique.

difficult. If the DO standard is near saturated conditions, certain aeration techniques may not be capable of meeting the deficit. For example, a natural turbine venting system might increase the DO levels as much as 3 mg/L or more when the incoming DO is low (0-1 mg/L) and the saturation value is high (10-11 mg/L). However, the same venting system may only transfer 1 mg/L or less if the incoming DO levels are near saturation.

A second word of caution should be made regarding Table 2-3 and the temperature of the discharge. If the facility has a history of releasing cold, hypolimnetic water which has resulted in a downstream coldwater habitat, certain aeration systems may not be applicable. In particular, selective withdrawal (variable or modified inlet structures), epilimnion surface pumps, and reservoir destratification systems can result in discharge temperatures that are high enough to impact the downstream fishery. In this case, other aeration techniques must be considered.

Table 2-3 lists seven different aeration techniques, plus "Combinations". Each of these techniques will be briefly introduced in this section. More detailed material, including information for sizing the various approaches for a specific site is presented in Section 6.

Operational Techniques. Operational Techniques include approaches to aeration that do not include auxiliary devices except for gate control mechanisms or bypass valves. Operational Techniques could include a partial or complete shutdown of the generator when DO standards are not met, or passing all, or a portion of the water over the spillway or through an aerating valve. Even though Operational Techniques are generally poor economic alternatives[3], technically they can meet the deficits of all categories of Table

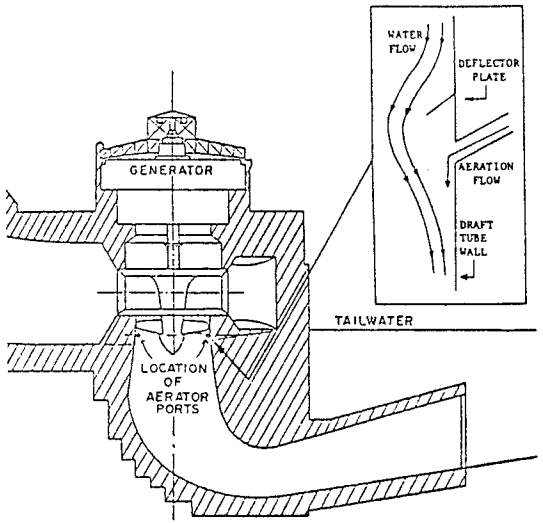
[3]If a self-aerating bypass system, such as a Howell-Bunger valve, is already in place, Operational Techniques can prove to be more cost-effective than other aeration techniques that must be installed.

2-3. Operational Techniques are more fully described in Section 6.4.

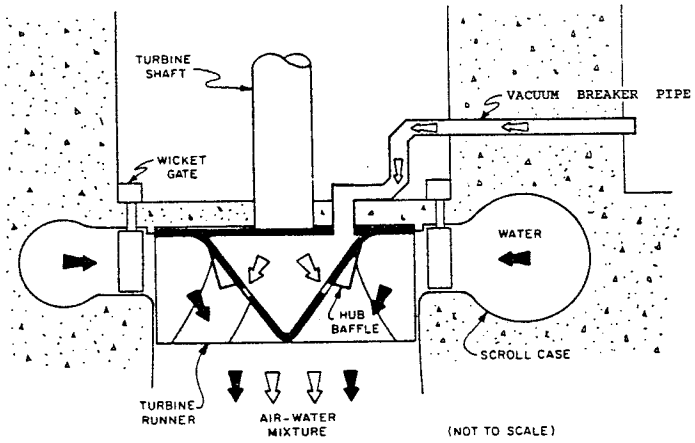
Weirs. Weirs are also suitable for each of the deficit categories shown in Table 2-3. Although the application of weirs solely for aeration of hydroelectric facility discharges has not been widely practiced, many years of data confirm that the operating characteristics of existing weirs make the application potentially attractive. Three drawbacks of weirs that generally lead to their elimination are: 1) the procedures for predicting performance are still being refined; 2) they are less feasible at low to moderate head dams; and, 3) they create a head loss due to an increase in tailwater elevation (unless constructed far enough downstream to minimize backwater). The substantial amount of data from existing river structures, however, indicate that weirs are capable of dramatic increases (4 mg/L or more during favorable circumstances) in dissolved oxygen with relatively small (3-feet to 4-feet) drops. Section 6.1 discusses weir applications and design.

Turbine Venting. Turbine venting (Section 6.2, Table 2-4), Figure 2-6, is one of the more popular aeration techniques, and, as such, offers a greater engineering database from which to predict performances. This is particularly true for systems that aspirate in the draft tube, just below the runner.

Even though performance of turbine venting systems is more predictable than other techniques, it is far from being 100% accurate. Some installations have achieved DO uptakes of less than 1 mg/L, while others have achieved transfers greater than 4 mg/L under ideal conditions (i.e., reduced gate opening). A safe, conservative estimate for the aeration increase that could be achieved with turbine venting systems is 1- to 2-mg/L, provided that proper site characteristics are present and proper guidelines for installation have been followed.



Through the Draft Tube



Through the Vacuum Breaker

Figure 2-6. Turbine Venting Techniques

When the dissolved oxygen deficit is 4 mg/L or more, turbine venting should not be relied upon as the sole aeration alternative, but should be considered in combination with other systems. Also, Table 2-3 illustrates, not all sites may be suitable for turbine venting applications. A runner located above the operating tailwater elevation is preferred, with aeration capacity dropping off as the runner's elevation falls below the tailwater. Turbine venting systems have been successful, however, with runners operating 12-feet or more below the tailwater. In all cases, draft tube velocities, port location, and baffle orientation are critical to an installation's success.

Table 2-4

ASPECTS OF TURBINE VENTING SYSTEM

Properly designed and installed, system can provide 1- to 3-mg/l increase in DO level

Design recommendations exist for draft tube venting systems

Venting systems are usually limited to a maximum of 4% air flow

Although not absolutely required, hydrostatic pressure below the runner should be less than atmospheric for venting to be successful.

Venting systems use baffles aligned with the flow to improve aspiration

Venting will reduce power revenues by 1% to 5%

Venting will reduce generation capacity

Approximately 8-weeks is required to install a venting system, if draft tube walls are vented

Aeration improves with reduced gate openings

A sub-set of turbine venting aeration systems is forced air injection from within the powerhouse. In this case, compressed air is forced into the system either through the headcover or into the draft tube. Compressors are used to overcome limitations presented by naturally vented systems (i.e., insufficient pressure difference to cause aspiration, or difficulty in routing large diameter supply piping to the turbine. Actual applications of this type, however, are fewer than naturally vented systems.

Selective Withdrawal. Some facilities include Inlet Structures, or Inlet Towers, that incorporate vertical gate slots. Depending on the particular design, it may be possible to retrofit these structures to allow water to enter at different elevations, taking advantage of the generally higher levels of oxygen contained in the epilimnion. As stated earlier, however, temperature restrictions, or a small-volume epilimnion may preclude use of this technique.

Occasionally, it may also be possible to retrofit the inlet tower to allow drawing water from two levels simultaneously. The mixed flow may meet both temperature and dissolved oxygen standards. In this case, however, the economics are seldom favorable, and alternative aeration techniques are generally adopted. Refer to Section 6.2 for further discussion of Selective Withdrawal Techniques.

Reservoir Aeration. Reservoir Aeration techniques include both destratification and gas injection systems. Successful reservoir gas injection systems for hydroelectric applications utilize diffusers supplied with pure oxygen to raise the DO level of either the hypolimnion or the water in the immediate forebay. Injection of air for the purpose of aeration, however, has not proven to be successful due to

the high cost and the potential risk of nitrogen supersaturation[4].

When lost power revenues attributed to the aeration system are high, and replacement generation capacity is being considered in the economic analysis, pure oxygen injection in the reservoir is often the most viable aeration alternative. Development of flexible membrane diffusers and the evolution of standard off-the-shelf designs for Pressure Swing Absorption oxygen plants have eliminated many of the disadvantages of earlier oxygen injection system. Refer to Section 6.3 for further information concerning Reservoir Techniques and oxygen injection systems.

Epilimnion Surface Pumps. The final aeration technique included in Table 2-3 is Epilimnion Surface Water Pumps. One of the earliest applications of using mechanical pumps to induce downward currents of oxygen-rich epilimnion water was by Garton in the 1950s. TVA has continued developing this method by placing the pumps in the forebay, and operating the units only when the turbines are on-line. This approach has worked well to aerate downstream discharges, although the initial cost for the installation is considerably more than other aeration techniques.

As in the case of destratification techniques, surface water pumps probably will be eliminated as an alternative if temperature restrictions apply. Additionally, the reservoir must also contain a sufficient volume of oxygen-rich epilimnion water to supply the turbines. Depending upon the degree of stratification, it is conceivable the epilimnion may be of insufficient volume and could become depleted. Section 6.2 presents additional information regarding surface water pumps.

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[4]Air injection techniques can be used successfully as mixing devices to destratify reservoirs. Rather than mixing a stratified reservoir, a recent approach has found that considerable savings result when mixing energy is applied at a time early enough to prevent stratification from occurring. Refer to Section 6.3 for further discussion.

2) Prepare Conceptual Design. Once Table 2-3 is used to screen inappropriate aeration techniques based upon site-specific technical viability, the next step is to prepare conceptual designs for the remaining alternatives. Performing a conceptual design and estimating the approximate size of the components for each technique will help to further differentiate the systems. The design will entail different exercises particular to each technique. For example, if hypolimnion oxygen-injection is being considered, the type and number of diffuser must be selected and estimated, along with the overall design of the distribution field. The number of diffusers will depend on the maximum oxygen demand (the greatest discharge flow at the greatest DO deficit) and the predicted absorption efficiency for the design. Distribution pipe size must be estimated, and the source of oxygen must be determined. If commercial oxygen (LOX) is being considered, size, type, and number of vaporizers must be included. When considering on-site oxygen generation, the costs of cryogenic versus Pressure Swing Absorption (PSA) systems should be compared. Refer to Appendix G for a discussion of the various aspects of using air or pure oxygen as a source for aeration, and a procedure that can be used to compare LOX, cryogenic plants, and PSA systems.

If a downstream weir is being considered, the topography of the tailrace, availability of materials, accessibility, and weir design are aspects that must be considered. Weir design will include overall layout, number of steps, height of steps, plunge pool depth, and, if the weir induces a headloss on the facility, a method of removing or lowering it during periods of non-stratification. For certain applications, the weir can serve not only to aerate the discharge, but also to re-regulate the flow and maintain downstream minimum flows.

Section 6 presents the particular procedures to use when performing conceptual designs for each technique. The individual discussions detail the numerous aspects that must be considered for each technique.

3) Prepare Preliminary Cost Estimate. A Preliminary Cost Estimate (Table 2-5) should be prepared for each conceptual design. The

Table 2-5

PRELIMINARY COST ESTIMATE

One-Time Expenditures:

- Equipment purchase
- Initial installation of electrical service
- Site preparation
- Field testing

Annual Costs:

- Operating labor
- Lost power revenues
- Operating energy costs
- Oxygen purchases
- Insurance
- Maintenance of aeration equipment
- Additional wear of turbine machinery or bypass valves
- Equipment rental

preliminary cost estimate for the initial installation should include equipment cost estimates for all components, excavation and site preparation, cost of lost power revenues that may occur during installation, and start-up procedures. If field testing is part of the final selection process, the associated costs should be included as part of the initial installation. The cost of the money used for the initial installation should also be considered.

Annual operating expenses should include any lost power revenues that may occur during the installation/removal of equipment (i.e.: weir removal; baffle installation), manpower to operate the system, maintenance, and items such as insurance. Energy costs may be considerable if compressors are part of the gas supply system. Operating costs based upon horsepower and hours of operation are relatively easy to estimate. The fact that the equipment is only

operated a portion of the year, and rarely at full capacity, should also be taken into account. The annual cost of insurance can be significant if the installation involves substantial amounts of mechanical equipment, such as in a cryogenic plant. However, for certain techniques, such as turbine venting, insurance is not a factor.

Annual maintenance normally consists of component rebuilding/replacement, painting, and/or cleaning. Certain pieces of equipment (e.g., compressors) will require major overhauls at periodic intervals of several years, and this cost should be estimated.

If oxygen is generated on-site, the cost may be included in the annual operating budget as an energy expense. If oxygen is purchased commercially, it should be included as a separate item to allow for price fluctuations to be evaluated in subsequent stages of analysis.

The cost of lost power revenues, along with another area that is not immediately obvious, that of replacement generation capacity, deserve special attention. If power generation capacity is reduced by the aeration system, the demand for this power must be met by other facilities, whether they be hydro, nuclear, coal, or other type of generating plant.

The cost of building power plants can range from $500 to $1,500 per kilowatt (Ref. 2-4). Designers must set a per-kilowatt-hour value which includes cost of lost generation revenues and replacement generation capacity. The possible range for this figure has an impact on the final selection of aeration technique. EPRI has suggested the use of $0.06/kWh to cover the costs of these effects for this study.

A final area that must be estimated is the cost of additional wear on existing powerhouse equipment. For example, turbine venting through the vacuum breaker may increase cavitation damage of the runner; bypass systems will accelerate the wear of gates and valves; oxygen injection in or near the powerhouse and upstream of the runner may result in accelerated deterioration due to corrosion. The accelerated deterioration will increase maintenance costs and possibly decrease power generating revenues. To estimate the cost of these effects depends on site-specific circumstances. If the runner is high-grade stainless steel, accelerated corrosion will not likely be a problem. If a cast steel runner is used with vacuum breaker venting, cavitation damage may initially increase 5-fold. Gate wear will depend upon the operating characteristics of the facility. Each of these effects are discussed with their respective techniques in Section 6.

When comparing the economics of aeration techniques, two basic approaches are often used. The first is to estimate all costs as they will occur, and amortize them into an equivalent series of uniform annual payments over the life of the system. Another method is to estimate the costs as they will occur, and reduce them to a single Present Worth value. The total of all Present Worth values is then used to compare the aeration techniques. The Present Worth approach has been adopted in this report, and is detailed in Appendix F.

4) Conduct Sensitivity Analysis. After calculating the preliminary cost estimates of the candidate designs, only one or two probably will remain as economically viable. At this point, the conceptual designs for each alternative should be fine tuned into a feasibility design, and the economic analysis repeated. The economic analysis should now include closer estimates for the equipment, and a test for sensitivity of the major economic factors. Sensitivity analyses are performed to establish the potential range of the total expenditure. As a minimum, sensitivities tested should include the cost of money (Capital Recovery Factor), equipment life expectancy, the effect of different transfer efficiencies, a change in the DO requirement, the cost of oxygen (if purchased commercially), and the effect of varying the cost of lost power revenues.

5) Assess Environmental Side-Effects. An additional consideration that should be considered is that of environmental side-effects. For example, if compressors are used to provide air or oxygen, noise may be a problem. The cost of repressing the noise should be estimated. If the noise cannot be reasonably suppressed, it may be necessary to choose another technique. Again, detailed discussions in Section 6 address the various environmental side-effects that may occur for each aeration technique.

6) Quantify Level of Confidence. An important element selecting the final technique is establishing and comparing the Levels of Confidence. The Level of Confidence is an assessment of each technique that considers the risk of a system working successfully. Because it is more of a qualitative measure, Levels of Confidence can only be quantified by the applicant or the design engineer, based upon their knowledge of equipment reliability and the experiences from other owners and experimenters who have worked with similar systems.

7) Assess Combinations of Techniques. A particular technique may be limited in its ability to transfer oxygen and incapable of always meeting the standard at a particular site, but may be considerably less expensive to install and operate than other systems. This less expensive system could be used to treat the initial deficit, with a secondary back-up system available for use when the DO deficit is too great for the primary system to meet. The secondary system may, or may not be sized to meet the full deficit. The optimum combination of two or more aeration techniques will need to be assessed based on conceptual design analysis, cost impact, and technical viability. Section 6 presents some of the better combinations to consider.

Once the conceptual and feasibility designs have been prepared, the cost analyses have been screened, selection of the final technique or combination of techniques can be made. If not already involved, an engineering consultant familiar with the various alternative designs and risks should be introduced to the project. While many utilities possess in-house engineering capability, individuals experienced with discharge aeration techniques maximize the probability of technical success. An experienced consultant should be considered to either review the proposed concepts or prepare the final design. It may

also be prudent to have the consultant's expertise available during preliminary field tests, installation of the permanent system, and start-up.

8) Perform Field Testing. Field tests of "scaled-down versions" of chosen techniques can provide valuable site-specific information and design guidelines for the full-scale system. Field testing will also serve to ascertain the level of confidence. Requirements for field testing will vary significantly depending on site-specific conditions and the aeration methods to be tested.

Continued Monitoring and Reporting

Once the aeration system is operational, monitoring of system performance should be initiated. The basic parameters to be monitored will be specified in the license. As a minimum, flows, dissolved oxygen levels, and temperatures should be recorded. The aeration system should be periodically inspected for increased equipment wear and/or decreased transfer efficiency. It is also recommended to monitor reservoir inflows and yearly stratification to observe any changes that may occur. Without continued monitoring of the reservoir, conditions could gradually worsen, undetected, and the facility would unknowingly be paying to correct poor water quality conditions that have resulted from upstream discharges.

Section 3

DESCRIPTION OF THE PROBLEM

Dissolved oxygen (DO) concentration in water has long been a significant concern in water quality management. DO is a fundamental requirement for surface water biological systems and a significant resource which allows rivers and reservoirs to assimilate treated wastewaters from municipal and industrial operations. It is a resource that occurs naturally in rivers and lakes and typically is used as an important measure of general water quality of surface waters.

All impoundments affect DO. DO depletion in some reservoirs may not be severe enough to substantially affect aquatic life, while other reservoirs affect DO significantly and routinely release water seasonally low in DO. Still, other reservoirs occasionally have low DO concentrations in the releases, but not every year.

Many factors affect DO concentrations and it is useful to identify these factors for each reservoir. Such information can be used in the selection of mitigating approaches, including reservoir operational changes. Another reason to learn more about DO at specific projects is to assess the potential for other water quality constituents that may result from low DO. For example, hydrogen sulfide is sometimes associated with very low DO concentrations and can be toxic to aquatic life. Iron and manganese are constituents sometimes associated with low DO and can consume DO added by aeration systems, contribute to slime growths in turbine systems, and impact water supplies.

DO is a responsive variable that is the result of a delicate balance between both oxygen producing and consuming processes. Natural sources of oxygen are the atmosphere and photosynthetic activity of aquatic plants, including algae. The atmosphere is generally the most significant source and in conjunction with water temperature

serves as the dominant factor that affects the saturation concentration of dissolved oxygen in water. Whenever the DO is less than saturated, it is not in equilibrium with the atmosphere, and the water absorbs oxygen from the atmosphere. Although it usually serves as a source of oxygen, the atmosphere will also serve as a "sink" if the DO is supersaturated. Major DO consumption processes include: (1) the decomposition of organic substances (dissolved, suspended, and settleable organic matter) from nonpoint sources, municipal and industrial wastewaters, and natural sources; (2) algal respiration associated with photosynthetic activity; (3) nitrification, which is the oxidation of ammonia and nitrite to nitrates; and, (4) oxidation of iron when it is present in a chemically reduced state, such as occurs in some cases near reservoir sediments.

The balance between the natural sources of oxygen and the consumption of DO is dependent on a number of variables such as the rates of various microbiological processes; contact between water and the atmosphere, which is dependent on hydraulic characteristics such as turbulence in flowing water and density currents in standing water; morphology and substrate characteristics; nutrient availability for algae and aquatic weeds; meteorology, especially wind speed, temperature, atmospheric pressure, and solar incidence; and toxicants which can suppress microorganisms involved in consumption processes and photosynthesis. As a result of the balance between sources and sinks and their responsive nature to these independent variables, the dissolved oxygen level in water is obviously very site-specific.

For reservoirs, it is useful to separate the factors that affect DO into two groups: (1) reservoir factors, and (2) watershed factors. Generalizations can be drawn to describe how these factors affect DO and to estimate DO levels that can be anticipated in the releases from various types of projects. However, the only way to quantify the DO levels at specific projects is to collect and analyze site-specific water quality data, sometimes using a water quality model.

3.1 RESERVOIR FACTORS THAT AFFECT DO

Hutchinson (Ref. 3-1) states that "a skillful limnologist can probably learn more about the nature of a lake from a series of oxygen

determinations than from any other kinds of chemical data." Hutchinson presents the history of DO studies in lakes, which date back to the turn of the century. In the late 1930s, Wiebe (Ref. 3-2, 3-3, 3-4, 3-5) reported the first DO information on a hydropower reservoir. Churchill (Ref. 3-6) documented the effects of several storage impoundments on water quality and illustrated the nature of DO variation in various types of reservoirs used for hydropower. Churchill reported the effects on DO of large inflows to impoundments as well as the effects of various outlet depths, and illustrated many differences between lakes and reservoirs. For the past two decades, the Corps of Engineers, Bureau of Reclamation, TVA, EPA, and other organizations have conducted or sponsored limnological studies at various impoundments in the United States, progressing to the point that two-dimensional computer models are now being used to simulate DO in reservoirs.

Hydropower reservoirs are considerably different than lakes and most other types of impoundments. A discussion on these differences as they affect DO is presented in Appendix C. In addition, a literature review on the historical development of the understanding of DO dynamics in hydropower reservoirs is included therein. The following discussion summarizes the factors that affect DO in hydropower reservoirs, along with the collective knowledge and experiences of various reservoir investigators.

Reservoir processes that affect DO are significantly influenced by the physical characteristics of reservoirs. Probably the most significant characteristics are the volume and through-flow of the project, which can be represented by the calculated retention time (summer volume/average flow rate) of water in the project. "Mainstem" projects (for the purpose of this paper, mainstem projects will also include run-of-river projects) typically have retention times of less than about 25 days; storage projects typically have retention times greater than about 200 days. "Transitional" projects have retention times that fall within the range of about 25 to 200 days. These classifications of projects will be used throughout the remainder of this section.

Thermal Stratification

Retention time and depth of outlet are the main factors that affect thermal stratification within reservoirs, which, in turn, affect the routing of "density currents" through reservoirs. An understanding of these density currents is important to determining how DO is affected at various locations within reservoirs.

Figure 3-1 illustrates typical temperature profiles depicting annual stratification patterns for various types of hydropower reservoir projects. Thermal stratification begins when the reservoir surface water warms and floats on top of the colder water in the reservoir. Figure 3-2 illustrates the relationship between density and temperature of water. The warm, top layer is called the epilimnion. A zone of transition develops between the epilimnion and the cold bottom water and is called the metalimnion. The isothermal cold bottom water is the hypolimnion. As the warm season progresses the epilimnion enlarges due to solar incidence and mixing caused by wind energy. The metalimnion also increases in volume due to the withdrawal of hypolimnetic water through the turbine outlets, and the spring and summer inflows which are cooler than the epilimnion but warmer than the hypolimnion. These inflows seek an appropriate water depth in the metalimnion having a density somewhere between the epilimnion and the hypolimnion. The metalimnions and hypolimnions in hydropower reservoirs are very dynamic due to the relatively high flows through these projects and the use of lower level outlets. It's in these two layers where density currents occur and DO is dominated by consumption processes and not replenished by the atmosphere or algal productivity.

In storage reservoirs, stratification is strong (large difference in temperature between the top and bottom) and persists through the summer and fall. Quite often the colder water that is in the reservoir originally during the winter may remain until the next fall. This is especially true if the outlet is at a mid-level point within the reservoir and the withdrawal zone does not extend to the reservoir bottom.

In transitional reservoirs thermal stratification is somewhat weaker than for storage impoundments because the cold winter inflows are

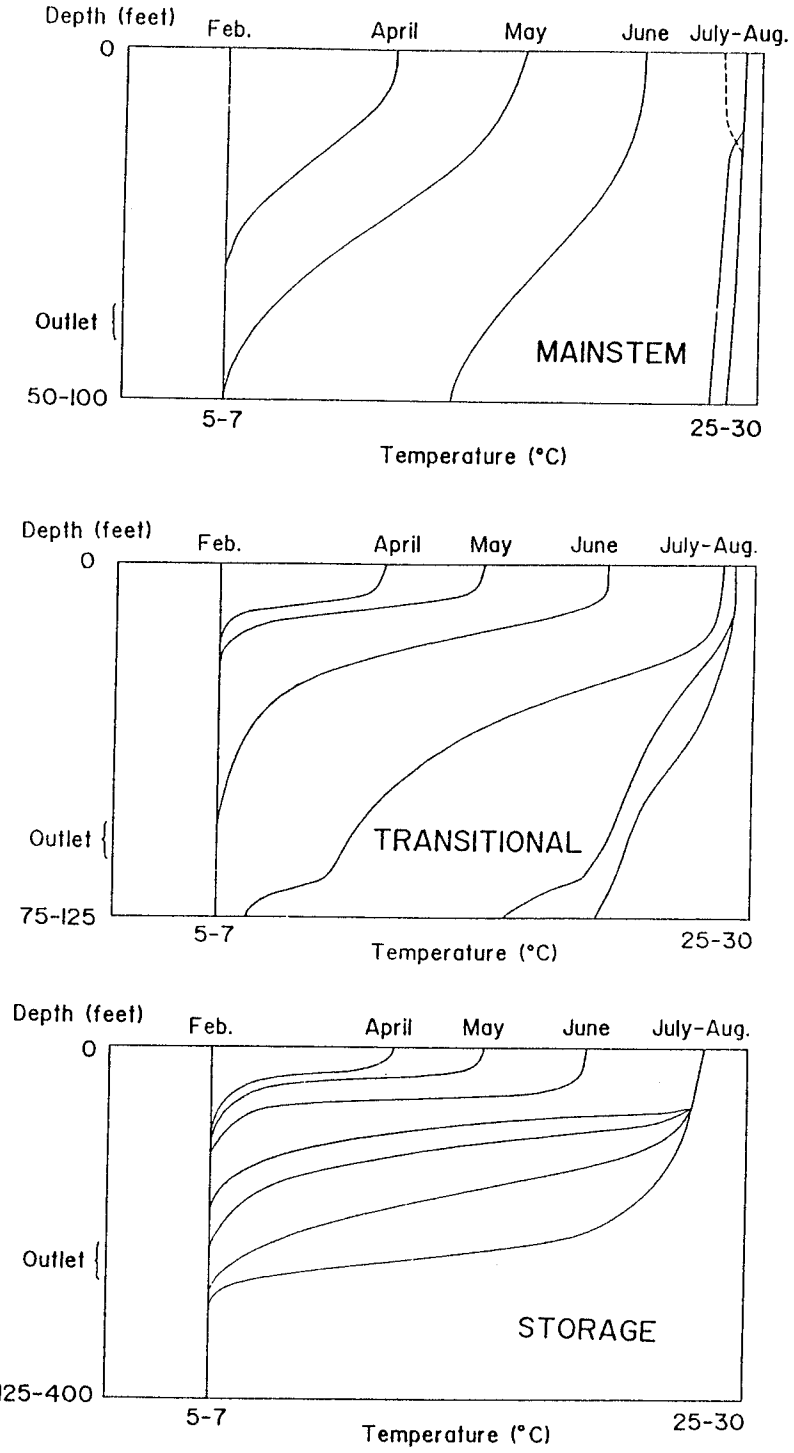


Figure 3-1. Typical warming patterns for storage, transitional, and mainstream reservoirs. In each case, the epilimnion first begins to form. Then, as seasonal warming progresses, the metalimnion forms and enlarges until it occupies the withdrawal zone, in concert with the release of the colder water resulting from hydropower generation.

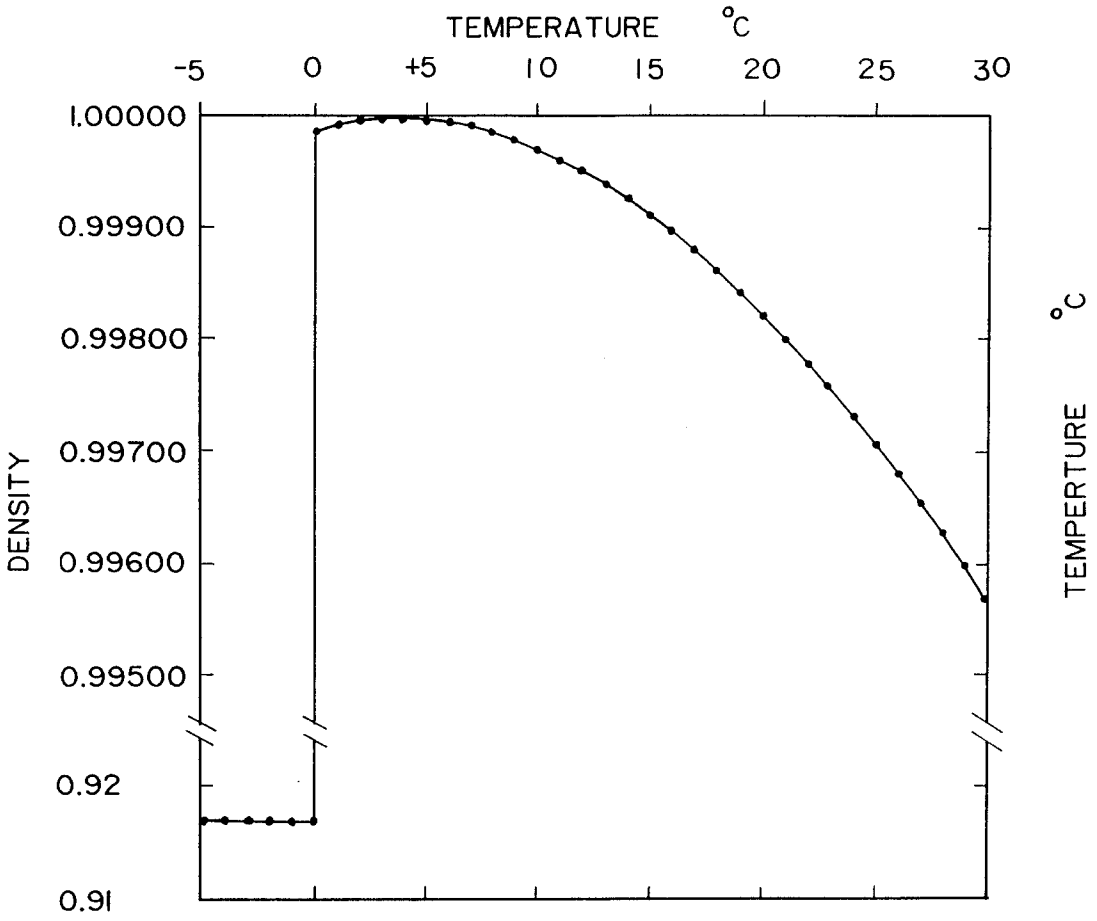


Figure 3-2. Density (gm/ml) as a function of temperature for distilled water at 1 atmosphere. Shows why the hypolimnion is typically equal to or greater than 4°C because water has its greatest density at 4°C. Warmer water has less density and, therefore, always sets above colder water, as long as salinity remains about the same. (Ref. 3-18).

released more rapidly from the bottom. This winter water is replaced by warmer inflow water as the warming pattern progresses into the summer and fall. Usually these types of reservoirs will maintain some form of stratification even though it will be weaker than that of storage impoundments. Transitional reservoirs which have storage impoundments a short distance upstream will not demonstrate this typical thermal pattern if the inflows remain to be cold through the summer and fall because the cold inflows drop beneath the warm surface and continue to maintain strong thermal stratification.

For mainstem reservoirs, the colder water is released even more rapidly and the resulting stratification is weaker, particularly in June, July, and August. Often during these latter two months stratification may not even occur, except under low flow conditions such as those that occur during droughts.

Environmental Processes in Reservoirs that Affect DO

The environmental processes that affect DO can be separated into three longitudinal zones and four thermal layers. The longitudinal zones include the riverine, transitional, and lacustrine zones. The thermal layers include the epilimnion, the warmer portion of the metalimnion which usually is composed of interflows that result from inflows to reservoirs during the months of May through September, the cooler metalimnion, which usually represents inflows during the months of March and April, and the hypolimnion. In areas of the U.S. where inflows are comprised of significant amounts of snowmelt, cooler inflows persist longer until about June. These zones and layers are illustrated in Figure 3-3 which shows that DO within a reservoir is usually low immediately above the sediments and in the warmer metalimnion, which occupies a comparatively larger portion of the reservoir.

As discussed in the previous section, the lower layers are density currents that essentially are isolated layers that do not mix in the reservoir until the temperatures of the layers become about the same as the epilimnion, usually in the fall of each year. Hence, to determine how the DO balance is affected in a reservoir, it is important to analyze the changes that take place in each layer of water. The longitudinal zones are useful for describing the changes

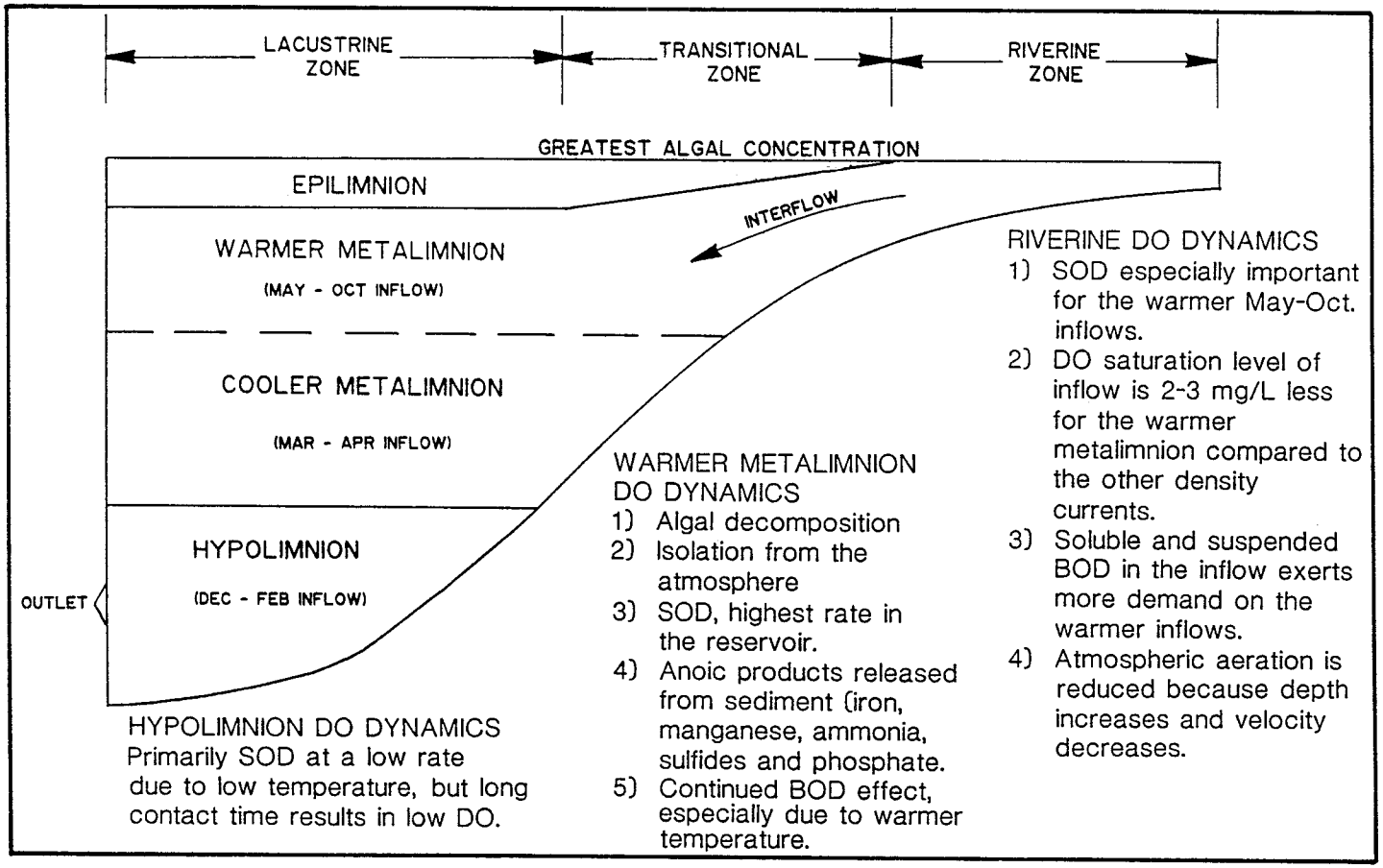


Figure 3-3. Zones and layers of a typical hydropower storage reservoir in the southern U.S., as they typically appear sometime during August through October. The density currents flowing through the reservoir include the hypolimnion, cooler metalimnion, and the warmer metalimnion. Over the period of spring through fall each year, they travel from the inflow to the low level outlet. The dominant processes that affect DO are depicted in the figure.

in water quality as the water passes through the reservoir. Table 3-1 presents a limnological description of the processes involved in these zones and the resulting DO dynamics.

Storage Reservoirs. In storage reservoirs used for hydropower, the epilimnion typically remains in the reservoir throughout the warmer months until fall turnover. This layer has high DO concentrations due to its contact with the atmosphere and solar radiation which allows photosynthetic generation of oxygen by algae. This layer is typically 20- to 30-feet deep until the temperatures of the warmer metalimnion, inflows, and epilimnion become the same level in fall, and then, this layer increases in depth. The dynamics of the epilimnion in hydropower reservoirs are significantly different than in most other reservoirs because water is rarely released from this level, especially in storage and transitional reservoirs.

In the coldest water layer and the cooler metalimnion where temperatures are less than about 12-13°C, oxygen consumption processes are retarded due to these lower temperatures. Hence, DO will remain in the water for long periods of time unless organic matter is present in relatively high concentrations. The level of DO in these two layers is also enhanced by their relatively high initial concentrations that are typically near the saturation levels, which are higher at the lower temperatures (Appendix G). As a result, the cooler metalimnion and hypolimnion usually have sufficient DO to provide for aquatic life, although the hypolimnion can have lower DO levels after it stays in contact with organic matter in the sediments for a sufficient amount of time. Even if DO is depleted near the sediments in these two layers, the volume of this low DO water typically is relatively low in comparison with the volume of the warmer metalimnion which is higher in elevation (see how unit volume increases with unit elevation for a typical storage reservoir, Figure 3-4). Also, the warmer metalimnion expands in depth as warmer inflows continue through the summer and early fall, and the colder layers are released.

The following scenario is typical for the mechanisms that contribute to low DO in warmer metalimnions of southern reservoirs: (1) pool levels are raised during March through June; and the increased pool

Table 3-1

CHARACTERISTICS OF THE RIVERINE, TRANSITIONAL, AND LACUSTRINE ZONES FOR MANY HYDROPOWER RESERVOIRS

	RIVERINE ZONE*	TRANSITIONAL ZONE*	LACUSTRINE ZONE*
MORPHOLOGY	Narrow, river channel	Broader, deeper basin	Deep, lake-like basin
HYDRAULICS	Lower velocity than natural river,but well-mixed; residence time, hours to days	Reduced velocity, becoming thermally stratified; but subject to mixing from-week-to- week, depending on changes in rate of inflow, temperature of inflow, meteorological conditions, and pool level changes. Residence time, days to weeks. Temperatures interflow similar to riverine zone.	Strong seasonal stratification. Hypolimnion volume decreases as releases are made, and metalimnion volume increases as summer inflows result in interflows. Residence time, months. Winter temperatures may persist at depths below outlet level throughout summer.
TURBIDITY AND SETTLING	Highest turbidity, suspended solids	Reduced turbidity, suspended solids	Relatively clear, low suspended solids
LIGHT PENETRATION	Lowest	Increased penetration	Highest light penetration
NUTRIENTS	Highest	High; some from sediments cycling into photic zone	Lowest
ALGAL PRODUCTIVITY	Biological Respiration exceeds algal productivity	Highest algal productivity	Algal productivity lower, due to limited nutrients
ORGANIC MATERIAL	Allochthonous, from streambeds, nonpoint and point sources	Allochthonous and autochthonous, the latter from algal growths	Primarily autochthonous, but lower in this zone
TROPHIC STATE	Eutrophic, sometimes hypereutrophic	From mesotrophic to hypereutrophic	Oligotrophic, sometimes mesotrophic
SEDIMENTS	Increased sediment oxygen demand caused by settling organic material	High sediment oxygen demand causing anoxia and release of Fe, Mn, PO_4, NH_4, and H_2S	Decreased sediment oxygen demand, sometimes causing anoxia and release of anoxic products
DISSOLVED OXYGEN	DO starts to decrease especially during warmer temperatures and low levels of inflow, caused by lower than natural velocities and greater depths; consequently less opportunity for atmospheric aeration and more opportunity for SOD to exert effects. Warmer temperatures reduce the saturation level of DO, thereby reducing inflow DO levels; warmer temperatures also increase biological processes that consume DO.	DO in warmer photic zone usually supersaturated; DO below thermal stratification decreases sometimes to anoxia starting in spring and progressively becoming lower as temperature increases; in early winter, colder inflows can enter with higher DO, as underflows. DO dynamics dependent on magnitude of flow, e.g., mainstem reservoirs often do not go anoxic. When anoxia occurs, often it occurs throughout the metalimnetic due to DO demand of the sediments and decomposition of organic matter in the water.	DO is usually high in the epilimnion. DO in the metalimnion, especially the portion greater than about 12°C, becomes depleted in reservoirs where water is isolated for long periods, i.e., about 90 days, and interflow volume is sufficient to reach to the dam. DO in the colder portion of the metalimnion and upper depths of hypolimnion usually remains high. DO near sediments often becomes depleted. As hydropower releases are made through the summer-fall, the colder waters with DO may be discharged from the reservoir, leaving only water with low DO to be released.

*These zones shift in location with changes in pool elevations, inflow rates, and channel geometry.

(Modified from Ref. 3-37, 3-15, and 3-38)

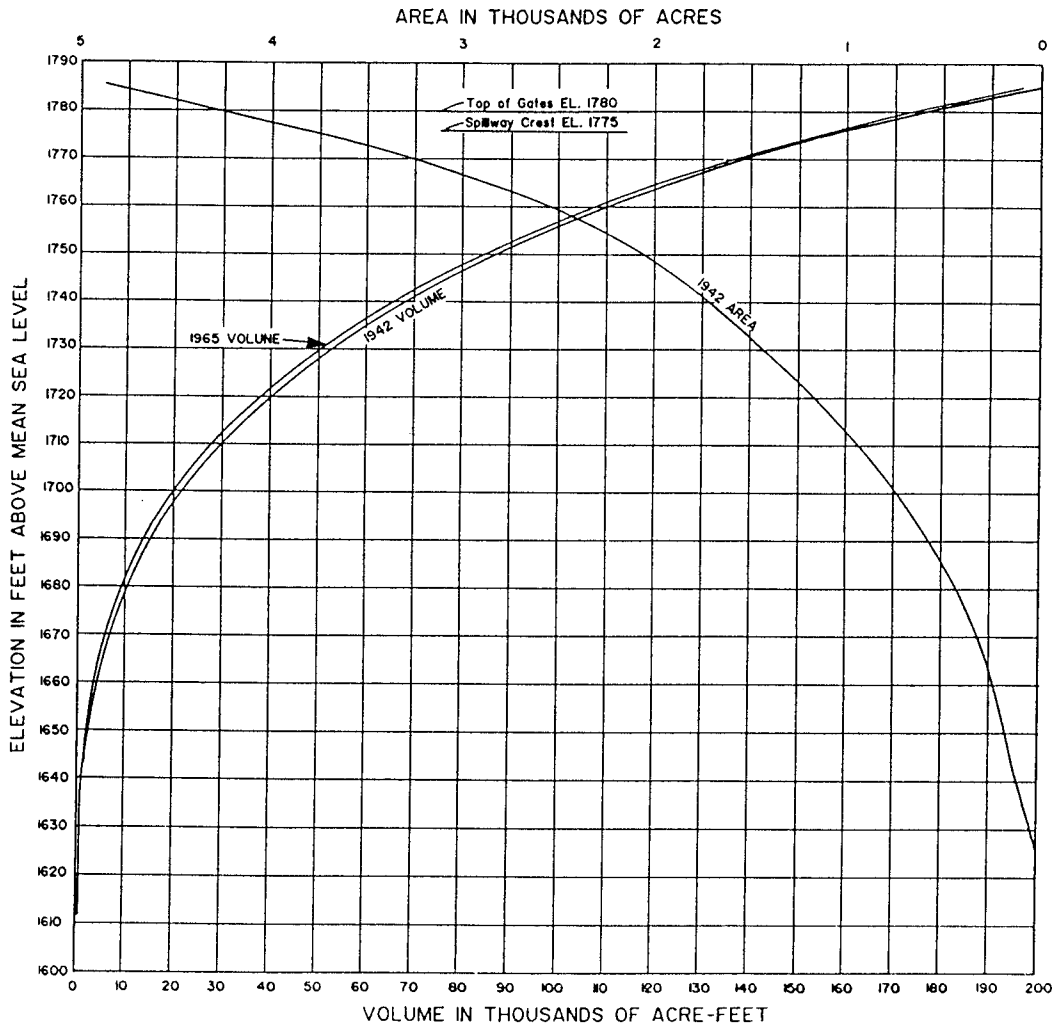


Figure 3-4. Volume and surface area of a storage reservoir for various depths or elevations. Shows that the unit volume per unit depth is much greater where the warmer metalimnion occurs in comparison with near-bottom waters.

levels cause backflow in the riverine zone, decreasing atmospheric aeration of inflow because of lower velocities and greater water depths; (2) inflow warms sufficiently during May and June so that the rates of oxygen consumption processes increase and DO saturation levels decrease; (3) inflow decreases as evapotranspiration in the watershed begins to dominate surface water hydrology; (4) lower inflow velocity and a longer riverine zone during high pool levels exposes inflows longer to the sediment oxygen demand (SOD); (5) algal growths in the epilimnion, especially in the transition zone, are the highest within the reservoir, and algae settle into the warmer portion of the metalimnion where they can exert significant DO demand; (6) warmer temperatures increase the rate of organic growths in the watershed during April through July and contribute to biochemical oxygen demand (BOD) in the warmer metalimnion; (7) interflows are isolated within the reservoir and not exposed to the atmosphere or photic zone to allow algae to produce oxygen; and (8) the warmer metalimnion remains in the reservoir until all colder water in the turbine withdrawal zone is released. This combination of events often leads to DO depletion in the warmer metalimnion, beginning in the transition zone and progressing down-reservoir to the dam.

The DO dynamics at each project usually vary from year-to-year due to variation in hydrological conditions. Figure 3-5 illustrates how DO in the warmer metalimnion in the forebay of Norris Reservoir progressed in a wet year compared with a dryer year.

Reservoirs having outlets higher in the forebay can significantly enhance the DO in the warmer metalimnion by reducing its retention time. On the other hand, some reservoir projects in the west have relatively long retention times (approximately 2-years) and do not experience low DO in the releases. This results from the fall turnover occurring before the low DO in the warmer metalimnion reaches the reservoir outlets. The length of the riverine zone in which an SOD is exerted on the overflowing water also can be a significant factor in comparing one reservoir with another. Another factor commonly used for assessing potential of DO uptake in lake metalimnions is the "shelf" factor which provides an indication of the amount of sediment area available to exert an oxygen demand. The significance of this particular factor for hydropower projects is

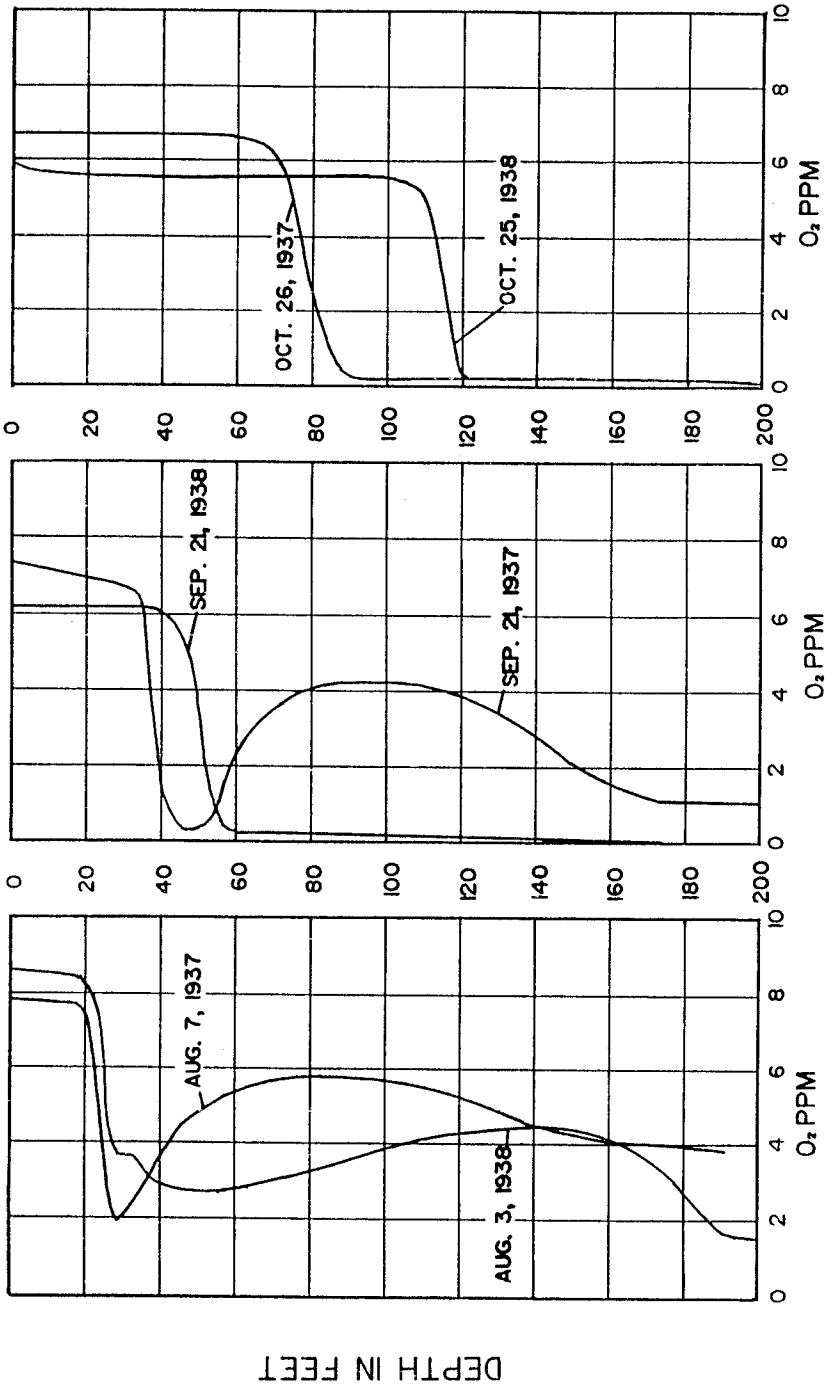


Figure 3-5. Forebay DO profiles from Norris Reservoir for 1937 (a low flow year) and 1938 (a wetter year). Shows how the high volume of flow in 1938 caused the warmer metalimnion DO (the upper level DO depression) to move more rapidly through the depths of the reservoir. In September, the cooler metalimnion DO (the level below the warmer metalimnion) persisted in 1937, whereas it had been released through the outlets by September in 1938. (Ref. 3-5).

probably somewhat lessened because of the relatively higher flow-through volumes of water in hydropower reservoirs compared to natural likes with relatively constant pool levels.

Transitional Reservoirs. Transitional reservoirs behave in a manner similar to storage reservoirs but have a more dynamic DO pattern. A metalimnion generally forms in the spring and perhaps early summer, but does not remain as an isolated volume of water as long as it would in a storage impoundment because the colder hypolimnetic water is released earlier in the summer season. In reservoirs with bottom level outlets, the warmer metalimnion eventually occupies the entire lower depths of the reservoir, and therefore, can be exposed to sediment oxygen demand throughout the entire length of the reservoir. This exposure to the SOD results in a greater DO uptake than occurs in the hypolimnion because of the warmer temperature in the metalimnion. The DO in releases from transitional reservoirs is not as sensitive to annual variations in flow-through volumes, pool level changes, and rates of release because the entire hypolimnion/metalimnion volume is generally replaced by inflows regardless of year-to-year hydrologic variation.

In transitional reservoirs with mid-level outlets, the turbine withdrawal zone (which usually extends down to about ten feet below the invert of the penstock intake) determines the elevation above which the warmer metalimnion remains. This elevation determines the length of contact between the warmer metalimnion and the sediments, and the retention time of the warmer metalimnion in the reservoir. The higher the relative elevation within the reservoir, the shorter the retention time and contact time with the sediments. The DO in the releases from these reservoirs may vary considerably from year-to-year depending on the variability of inflow hydrology. If the volume of colder water is released relatively rapidly, the potential DO demand can be reduced because the time the metalimnion spends in the reservoir will be reduced. On the other hand, low rates of release can result in lower DO levels because the metalimnetic DO demand has more time to exert itself.

Mainstream Reservoirs. For mainstem reservoirs, DO levels in the lower depths are a function primarily of the mass of DO in the inflow

and the retention time in the reservoir. The DO deficit in the releases is proportional to the retention time and indirectly proportional to the mass of DO in the inflow. In comparison with the other two types of reservoirs, DO dynamics in mainstem reservoirs are more sensitive to flow through the project. As an example, the DO levels in most Tennessee River reservoirs are not less than five milligrams per liter except under low flow conditions.

The transition zone that commonly occurs in storage reservoirs may occupy the entire length of mainstem reservoirs below the riverine zone. In these reservoirs, hydrometeorological conditions can prevail and be the dominate factor affecting DO within the depths of the reservoir. For example, it has been observed in Kentucky Lake on the Tennessee River that even with very weak thermal stratification, DO levels can occur on the order of two milligrams per liter. Some areas can even become anoxic. However, factors such as wind and internally generated waves caused by peaking hydropower operations can rapidly change the DO concentrations. Based on the application of computer models to mainstem projects in the TVA system, Brown, et al., (Ref. 3-7) reported that DO in the reservoir tends to be dominated by the inflow DO concentrations during higher flow periods. Under low flow conditions, internal DO uptake processes such as sediment oxygen demand and oxygen consumption due to algal respiration and decomposition of algae become dominant in affecting DO in the reservoir.

The metalimnion that forms in mainstem projects is short-lived and may occur only during low flow years. DO levels in the releases from mainstem reservoirs rarely become totally depleted and are thus considerably different than storage and transitional reservoirs.

Sulfide, Iron, and Manganese

Storage and transitional reservoirs with bottom level outlets are the most likely to experience anoxia (complete DO depletion) in the sediments throughout most of the reservoir where the main flow occurs. Under these conditions, chemical substances can be released from the sediments in sufficient quantity to be measurable in the releases through the turbines. The substances of most concern, as mentioned earlier, include hydrogen sulfide, iron, and manganese and

are released from sediments in the sequence shown in Figure 3-6. The occurrence of these products in turbine releases can vary from year to year depending on variations in runoff hydrology. At TVA's Douglas Project, sulfide was measured in the releases during an extreme drought year to be about 125 μg/L, but was only 1-3 μg/L the following year, which experienced record rainfalls. Biofouling in the turbine system has been attributed to high levels of iron and manganese (Ref. 3-8).

Factors Affecting DO at TVA Projects

To illustrate some of the above principles, major factors that affect DO in the releases from TVA hydropower projects can be evaluated in Figure 3-7. The factors are retention time, level of outlet, and the DO concentration in the warmer metalimnion. Figure 3-7 presents the median and minimum annual low DO levels from 18 years of weekly data for 26 projects. Average retention time was calculated using average annual flow (except for mainstem projects where average summer flows were used) and the volume at normal maximum summer pool levels. Metalimnion DO levels were determined using data collected intermittently for various purposes over the period of record. This figure vividly illustrates the effects that retention time, bottom-level outlets, and low (less than 2 mg/L) metalimnion DO have on the potential for low DO levels in hydropower releases. It is also interesting to note the range of annual variability in DO levels in reservoir releases from some projects. Such variability is important for the aeration system designer to keep in mind if the project has only limited historical DO data.

From Figure 3-7, the projects that have the lowest DO in their releases are transitional and storage projects with bottom level outlets and low metalimnion DO (less than 2 mg/L). The projects that have mid-level outlets but have low metalimnion DO also have relatively low DO in their releases, although somewhat higher than those with bottom level outlets. All the other projects with mid-level outlets fared better with respect to DO levels. All the mainstem projects had median low DO values greater than 3 mg/L, but here again the projects with bottom level outlets had lower DO levels, especially for the minimum observed DO.

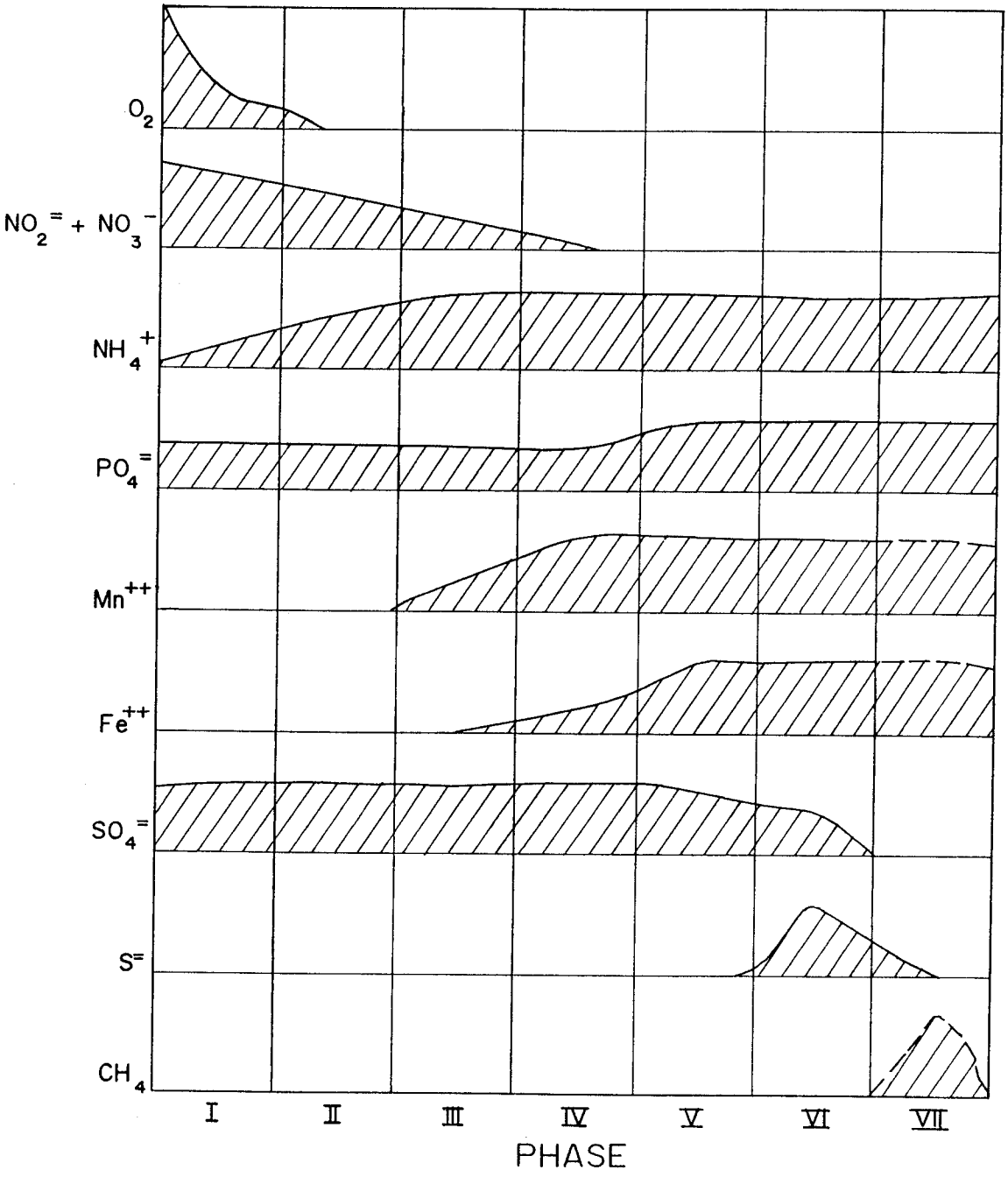


Figure 3-6. Sequencing of releases of chemical substances under anoxic conditions. (Ref. 3-19). The extent of the progression through this sequence is affected by many variables, but the amount of organic material present is the main driving force.

Kennedy and Gaugush (Ref. 3-9) summarized information on U.S. Army Corps of Engineers hydropower projects that appears to be consistent with Figure 3-7. They reported that reservoirs with relatively shallower depths of low DO tend to have lower DO concentrations in their releases, whereas reservoirs with anoxia limited to deeper waters "tend to exhibit acceptable dissolved oxygen conditions in their tailwaters". They reported that the reason for these observations was that their turbine intakes are generally located at mid-level.

3.2 WATERSHED FACTORS THAT AFFECT DO IN RELEASES

From the previous discussion, it is obvious that the amount of precipitation and inflow temperature variation affect thermal stratification, but other factors can also be important. For example, the size of the watershed draining into the reservoir affects not only the amount of flow through the reservoir but the natural organic loading and nonpoint sources to the reservoir as well. Precipitation intensity and frequency also affect the transport and timing of watershed water quality constituents such as organic matter. Since thunderstorms occur more frequently in the southeast (Ref. 3-10), the reservoirs in this region may receive greater loads.

Groeger and Kimmel (Ref. 3-11) referenced one study where 40 percent of the annual allochthonous organic matter input to a mainstream Michigan reservoir entered and flowed through the system during a 4-week period of high spring flow. Wastewater discharges and nonpoint sources affect the characteristics of the inflow. Another consideration is the effect of a system of reservoir projects which can act to increase DO if the upstream projects retain organic substances and nutrients from the upstream watershed. On the other hand, dissolved phosphates are released from some reservoirs and are more readily available for contributing to greater algal growths in downstream projects (Ref. 3-12).

Terrestrial characteristics in the west can result in lower contributions of organic matter from runoff. This reduced loading, however, can be offset by increased contributions from stream growths that occur over more extensive stream/river systems in the relatively

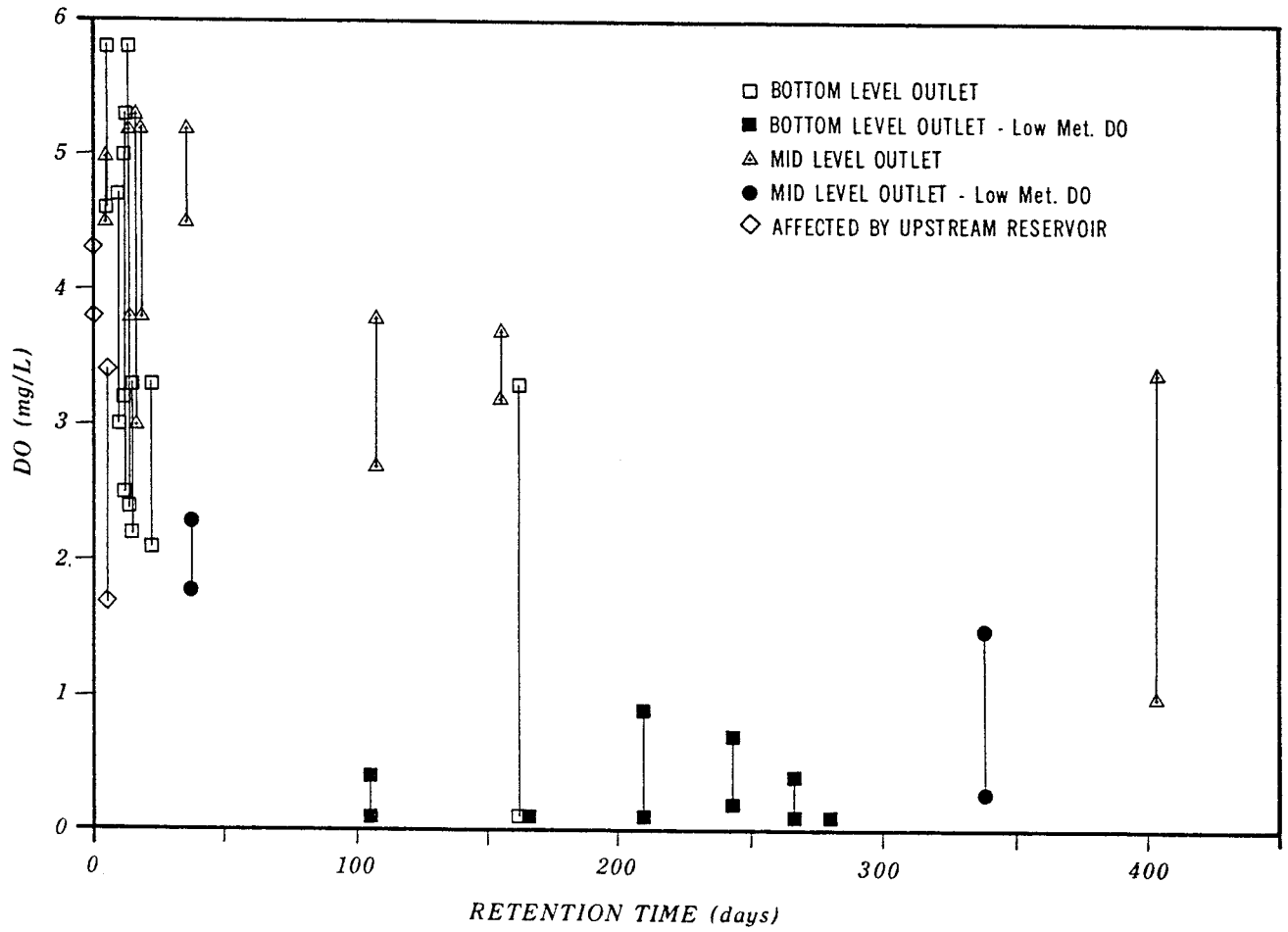


Figure 3-7. Annual low DO characteristics (represented by the median and minimum of the lowest annual DO measurements -- taken weekly -- over a 20-year period) for TVA reservoirs with average retention times ranging up to 400 days. The figure shows that retention time, level of outlet, and DO level in the metalimnion significantly affect the level of DO in releases. Annual variation in retention time affects the annual variation in DO as shown in Figure 3-9.

larger watersheds in the west. Based on information from the Corps of Engineers, Bureau of Reclamation, and TVA (Ref. 3-13) and Cada, et al., (Ref. 3-14) a greater percentage of projects in the east were found to have low DO in the releases from hydropower projects.

Regarding streamflow, upstream reservoir projects significantly alter the natural hydrologic runoff, e.g., high spring natural runoff quantities can be shifted to late summer and fall high volume reservoir releases. Such a shift in flow quantity significantly affects downstream reservoir processes affecting DO.

Another significant factor to assess is the dominant source of inflow. The typical storage impoundment will have one or two primary sources of inflow, accounting for 70 or more percent of the reservoir inflow volume; however, some impoundments can have significantly dispersed inflow quantities coming from multiple tributaries, e.g., the inflow to Chatuge Reservoir (TVA) through its primary source the Hiwassee River accounts for only 40% of the inflow. Such dispersed inflows can complicate significantly the reservoir processes that may affect DO within a reservoir.

Temperature in the inflow can be significantly altered by an upstream steam plant or an upstream hydroelectric power-plant with low level releases. These two types of operations, of course, have different effects on the temperature of the inflow water, but they also have a significant effect on the thermal layer to which they flow. Boone Reservoir (TVA) is significantly influenced by the cold water inflows from two upstream hydroelectric power projects. The reservoir has a continual flow of essentially unlimited cold water throughout the summer and fall months and the warmer metalimnion remains essentially isolated throughout this period of time without being drawn through the outlets. The biological DO uptake rate can double with an increase in temperature of about 10°C.

Reservoirs having watersheds with significant snowmelt during the spring can exhibit the same DO dynamics seen for southeastern reservoirs. However, these dynamics will lag in time corresponding with the temperature and peak inflow hydrology that is characteristic in the northern regions. In the south, the peak inflow hydrology is

dominated by more direct runoff from spring rains which occur during March through May.

Various nonpoint sources of contamination, particularly that from agricultural sources, are suspected of affecting DO in some TVA impoundments, and in some cases could be the incremental load that causes hydrogen sulfide in the releases. BOD levels of inflows can be highly significant in terms of the potential for consuming considerable amounts of DO within the water. Fine particulate organic matter has been observed to stay suspended within interflows for extensive distances within a reservoir. Coarser particulate organic matter is suspected of settling in the riverine and transitional zones of the reservoir and exerting sediment oxygen demand. Dissolved organic matter accounts for a significant portion of the mass of organic matter entering the reservoir, however, Kimmel (Ref. 3-15) suspects the DO uptake by dissolved organic matter is much less than otherwise may be suspected because much of this material is considered refractory. Groeger and Kimmel (Ref. 3-11) referenced other findings where autochthonous organic matter (typically algal growths) was generally believed to have higher energy and nutrient content per unit weight and to be more biologically labile than allochthonous material. More data are needed on oxygen consumption associated with organics.

Nitrogen and phosphorus are also significant considerations. Soluble phosphorus is a special concern because it is readily available for algal uptake. Nitrogen often is in a dissolved form that is readily available to algae. Suspended phosphorus usually settles to the sediments. However, this phosphorus can be released into the overlying water if anoxic conditions occur. In addition to examining water quality data in the inflow to the reservoir, it is useful to assess information on land uses within the upstream watershed as well as data on wastewater discharges. Also the size of the watershed and the associated annual streamflow can be a significant consideration in that in relatively larger flow systems, the natural loads of organics and nutrients may be sufficient to result in depletion of dissolved oxygen in such reservoirs. On the other hand, additional manmade loads may aggravate a low DO problem to the point that

undesirable anoxic constituents such as hydrogen sulfide, iron, and manganese are also released through the turbine discharges.

Consideration for Watershed Management to Increase DO Levels

Pertinent man-induced inflow characteristics that affect DO and that can be controlled include organic material (BOD), ammonia, and nutrients that control the growth of algae and aquatic plants. Models can determine fairly reliably the effect of BOD or ammonia on DO consumption, but determining the effects of nutrients on algal growths and subsequent oxygen consumption is much more difficult because of the uncertainty associated with so many environmental processes. For example, phosphorus generally settles into the sediments of reservoirs and cycles back into the water column under anoxic conditions, becoming available for algal growths following mixing events. Cooke, et al. (Ref. 3-16) reports that this internal loading of phosphorus is probably impossible to predict using a general rate of decrease for all lakes. Based on very limited documented experience, a 10-year period was reported to be necessary for a significant decrease in internal loading for lakes; however, recovery in 3- to 4-years was predicted for one lake which had a high flush rate. Of 28 lakes reported, only 12 improved in trophic status following diversion of wastes, thus indicating the importance of site-specific analyses instead of assuming reservoirs will improve with a reduction of organics and nutrients in the watershed. Another consideration is that the combination of natural inflow BOD and SOD may consume sufficient quantities of DO so as to account for enough DO uptake to deplete the oxygen resource.

TVA experience (Ref. 3-17) has shown that DO in hydropower releases can improve when BOD and ammonia are either substantially reduced or eliminated. Increased treatment for the City of Knoxville improved DO in the releases from Ft. Loudoun by about 1 mg/L. The closing of a paper mill resulted in a DO increase of about 2 mg/L in the releases from Fontana, and the closing of a chemical plant resulted in an improvement of about 2 mg/L in the releases from Ft. Patrick Henry Dam. These examples demonstrate that waste loads with organic materials and ammonia can affect DO in reservoir releases; however, it is important to note that these waste loads originally received only a small amount of treatment in comparison with today's effluent

standards. Modeling on Ft. Loudoun demonstrated that additional treatment beyond advanced secondary at Knoxville would not measurably increase DO above present levels in the releases.

Reduction of manmade nonpoint sources should eventually improve DO levels and/or reduce anoxic chemical products in reservoir releases. Such reductions can reduce nutrients, as well as organic materials and should be pursued. However, the benefits to DO improvement may not be realized for many years (i.e., although estimates are not available, one conceivable scenario is 5- to 10-years to implement NPS controls, about 5- to 10-years for the nutrients in streambed sediments to return to natural levels, and about 5- to 10-years for the excess nutrients to flush out of headwater impoundments). Nonpoint source control programs vary from state to state.

Geographical Considerations for Reservoir Projects With Low DO

While site-specific factors are the major consideration in determining DO concerns at a specific project, a national evaluation by Cada, et al., (Ref. 3-14) reported some useful findings with respect to geographical differences of the United States, the size of the hydropower operation, and seasonal considerations. They analyzed available DO data from the USGS WATSTORE system for reservoirs listed in the United States Army Corps of Engineers National Hydropower Study and determined the probability of occurrence of DO levels less than 5.0 mg/L. They computed a parameter defined as the probability of noncompliance (PNC) which is a statistic that relates to the chances of discharges below hydroelectric dams to violate a DO level of 5.0 mg/L. Their results are summarized in Table 3-2. In comparing the regions east of the Rockies with those west of the Rockies, they determined that the median PNC values for the West was practically zero, although a small number of reservoir projects apparently did violate the criteria as indicated by their reported maximum values for PNC.

Another significant finding from this study was the difference in PNC values for projects having a capacity greater than 30 MW compared with those less than this capacity. The PNC values for the larger plants east of the Rockies during the summer season had a mean of 0.315 compared with a mean PNC value of 0.092 for the lower capacity

Table 3-2

REGIONAL MEAN PROBABILITIES OF NONCOMPLIANCE
ESTIMATED FOR EACH CAPACITY AND SEASON

Region	No. of Dams	Mean PNC
	=< 30 MW, Summer Season (July, October)	
East of Rockies	41	0.092
West of Rockies	20	0.070
	> 30 MW, Summer Season	
East of Rockies	43	0.315
West of Rockies	28	0.038
	=< 30 MW, Winter Season	
East of Rockies	44	0.008
West of Rockies	19	0.004
	> 30 MW, Winter Season	
East of Rockies	45	0.055
West of Rockies	28	0.000

(Modified from Ref. 3-14)

plants. Finally, they reported that the PNC for "summer season" (July, August, September, and October) was significantly greater than that for the "winter season", even for the small projects in the northeast and Rocky Mountain regions where ice cover might be suspected as a potential problem.

These regional observations appear to be in agreement with findings reported by the Bureau of Reclamation, Corps of Engineers, and TVA (see Ref. 3-13). For example, the Bureau of Reclamation, which has practically all of its projects west of the Rockies, reported that about 8-percent of their reservoir projects have DO concerns other than occasional observations, the Corps of Engineers reported that about 18-percent of their projects (which are located throughout the United States) have concerns for low DO other than occasional situations, and TVA reported that 42-percent of their projects have low DO concerns other than occasional. It should be noted, however, that the percentage of hydropower projects in the TVA system is relatively high compared with the Corps of Engineers and the Bureau of Reclama-

tion. Studies by the Corps of Engineers at Vicksburg, Mississippi, have shown that releases through outlet structures other than hydropower usually result in significant increases in DO through the dissipation of energy immediately below the dam or within the outlet works. Therefore, if the Bureau of Reclamation and Corps of Engineers data sets had been limited to hydropower operations, they may have reported higher percentages of low DO occurrences.

Another study by the U.S. Corps of Engineers by Kennedy and Gaugush (Ref. 3-9) presented further information on the DO conditions below their hydropower projects, located predominantly in the southeast, along the Missouri River, and in the northwest. They grouped the projects under three classifications: "severe" if concentrations were routinely below the standard; "moderate" if they occurred on an infrequent basis and "not problematic" if they were never below the standards. The results are shown in Figure 3-8. Of their 73 projects, 17 are considered "severe" and seven are considered moderate -- all of these are in the southeast. Ten projects in the southeast are considered "not problematic".

3.3 FACTORS THAT AFFECT TAILWATER DO LEVELS

DO in the tailwater is affected primarily by characteristics of the hydropower releases, various tailwater hydraulic conditions, the presence of aquatic weeds, and various DO consumption processes. Mechanistic formulations for riverine DO predictions can be found in a comprehensive review by Bowie, et al. (Ref. 3-20). A qualitative description of the factors is provided here and quantitative descriptions are included in case studies presented in Appendix C.

Characteristics of DO in Reservoir Releases

Water quality in tailwaters is usually dominated by reservoir releases because of their volume. Hence, hourly operational characteristics can significantly change DO in downstream reaches and cause cyclical variations.

The variation of DO in releases depends primarily on DO changes in the reservoir, which depend to a large extent on the type of project. Storage reservoirs tend to have lowest DO conditions in the late

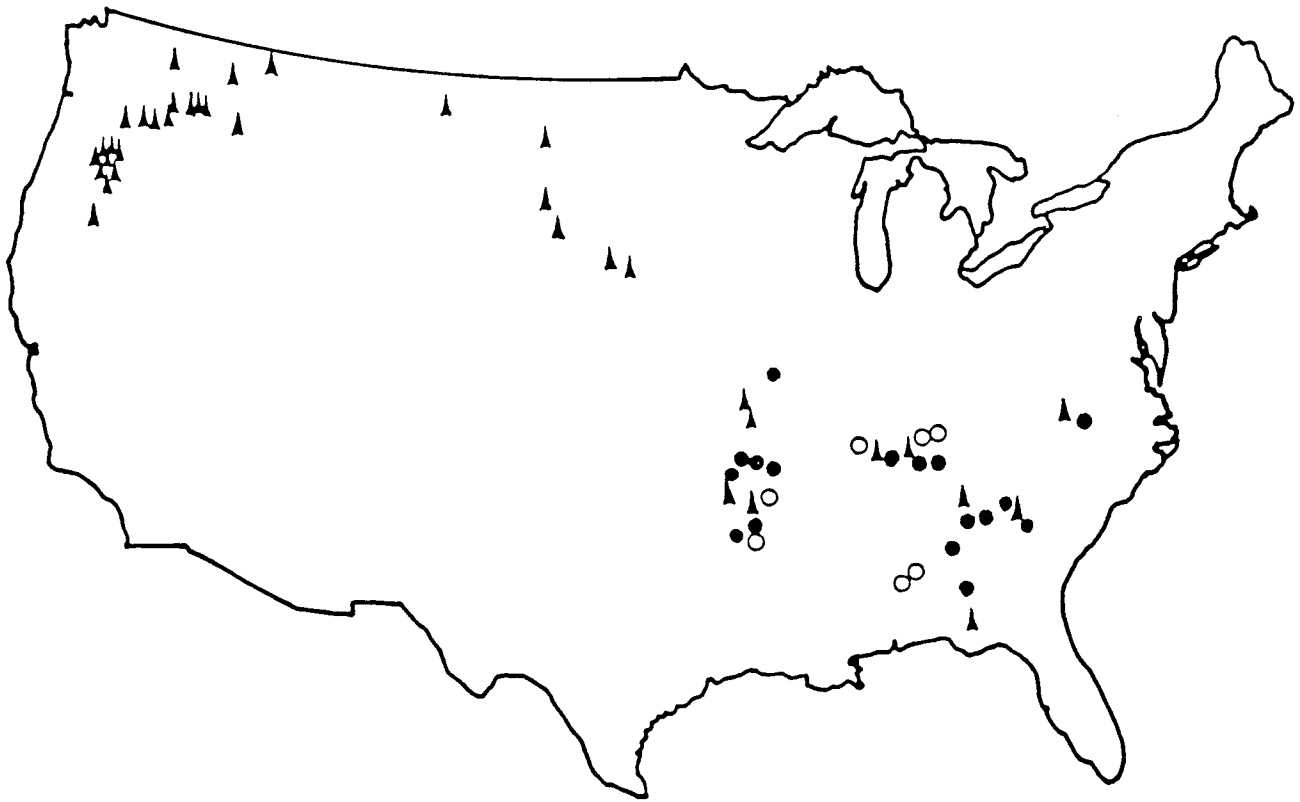
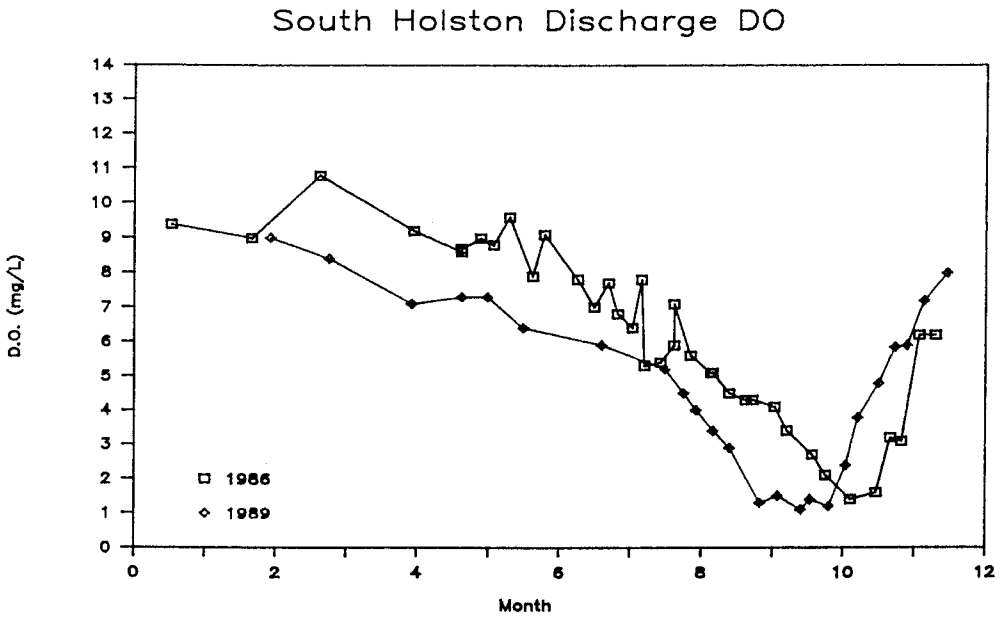


Figure 3-8. Distribution of 73 U.S. Army Corps of Engineers hydropower projects having severe (●), minor (○), and no problematic (▲) DO conditions in their tailwater. (Ref. 3-9)

summer and fall because of relatively long retention times, whereas transition and mainstem projects have lowest DO conditions during the summer. The pattern of DO in the releases may change year to year, primarily due to variations in hydrology and meteorology.

Figure 3-9 shows how DO varied during 1986 and 1989 at four storage projects and two mainstem projects. These two years were near-record drought and high rainfall years, respectively. These graphs vividly illustrate how DO varied over the course of the year, as well as how hydrology can affect DO in different types of projects. The South Holston and Watauga Projects have mid-level outlets, and the former usually has lower DO in the warmer metalimnion than the latter project. Also, the Watauga Project has a longer retention time. The result of these two factors in combination was that the Watauga Project did not experience a DO level less than about 6 mg/L during 1986, but did experience a low DO level of about 2 mg/L in 1989 when the increased volume of the warmer metalimnion was sufficient to reach the outlets. The minimum DO at South Holston was not much lower in 1989 compared with 1986, but the lowest DO occurred about six weeks earlier in 1989 and was generally lower the period beginning in March and extending to October. At Norris, the DO was about 2 mg/L lower in 1989 during June, July, and August, but increased rapidly in mid-September, either because the reservoir destratified earlier or the large inflows diluted the effects of the DO demands in the warmer metalimnion. The DO at the mainstem projects at Watts Bar and Chickamauga increased in proportion to flow, as expected for these types of projects.

Another consideration for DO variation in releases is the effect of hydropower operations. Turbine operations can significantly affect DO in the releases. For example, at Watts Bar Dam, a special study was conducted to determine the variation of DO concentration below each of the four turbine units as well as at various times after generation had been initiated. The results showed that the quantity of flow being released through the project (i.e., the number of turbines that were generating at any one time) affected the DO level because when higher flows were being released, the withdrawal zone in the reservoir was expanded to include more of the high DO water from the epilimnion. Another interesting observation was that the turbine



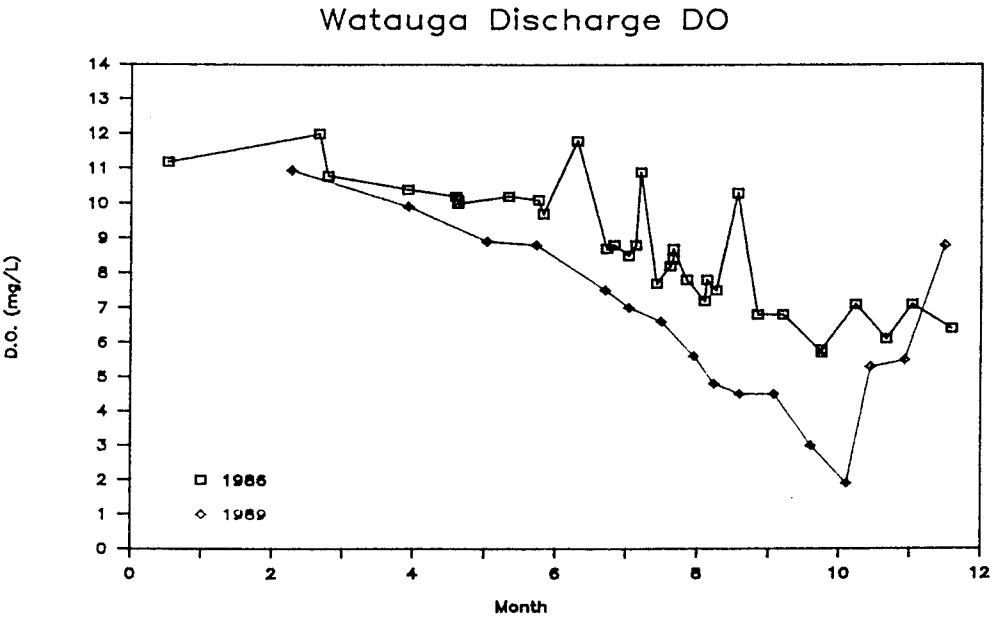
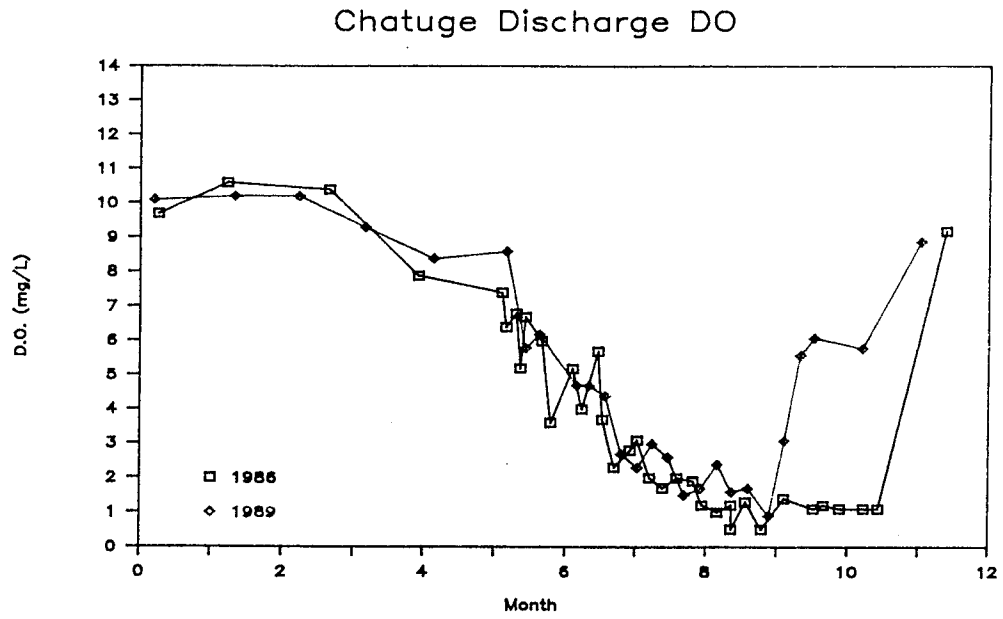


Figure 3-9. Variation of DO in the releases from several TVA projects, for a low flow year (1986) and a wet year (1989). Notice that at Chickamauga and Watts Bar (mainstem projects) DO was higher in the wet year, whereas at the other projects, DO was lower or about the same during the wet year.



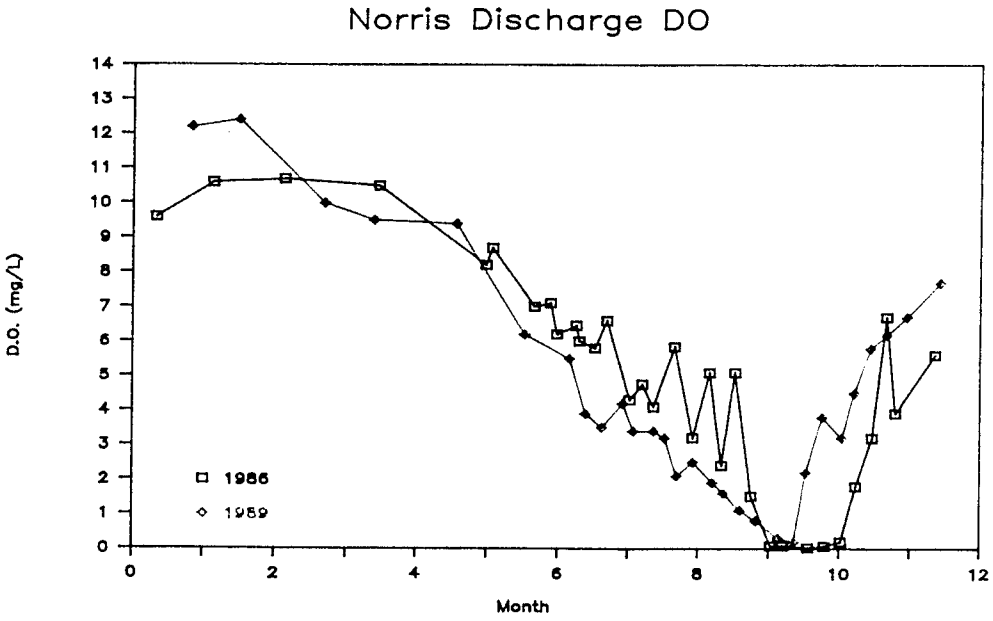
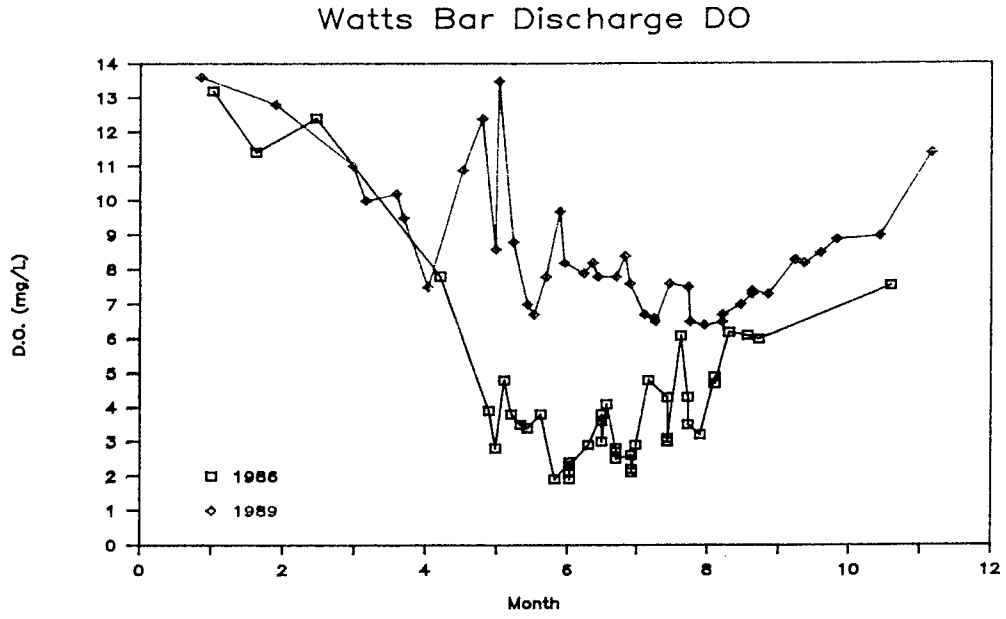


Figure 3-9. Continued.



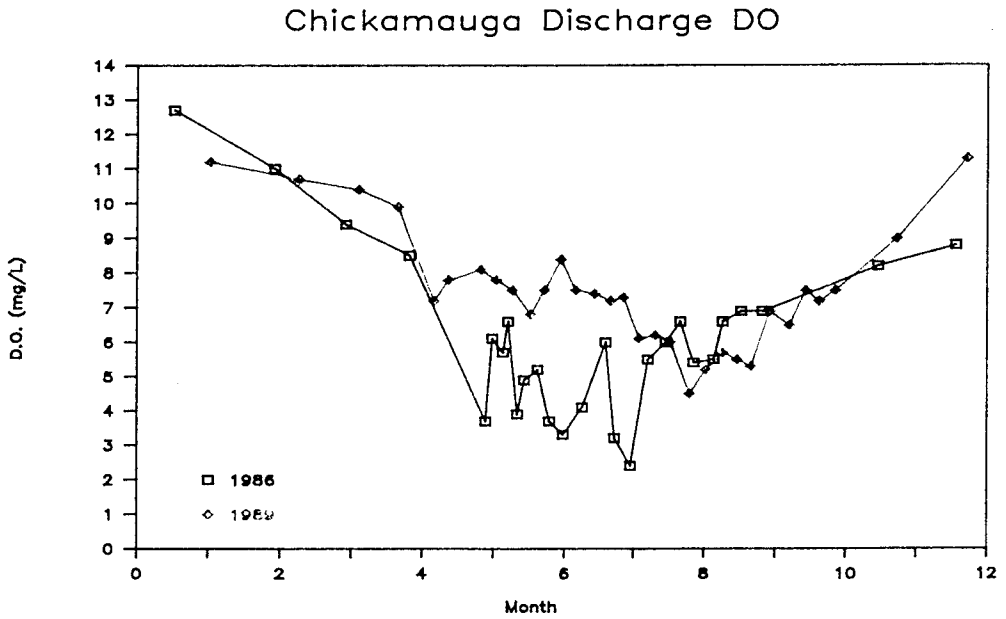


Figure 3-9. Continued.

releases nearest the right bank of the river had DO concentrations somewhat higher than the rest of the units.

Release flow and DO are often responsible for extreme variations in tailwater DO concentrations. If high discharges of low DO water occur suddenly during mid-day, overwhelming photosynthetic processes that are producing high DO concentrations, rapid drops in DO of several mg/L can occur in minutes, especially in the first few miles below the dam. Conversely, if flow is suddenly stopped in mid-day, DO concentrations may increase dramatically due to photosynthetic and atmospheric reaeration effects. High flows will dampen the effects of instream processes such as photosynthesis, reducing daily fluctuations in DO. However, alternating high and zero discharge (normal turbine operation) can produce wide daily fluctuations in DO, especially if the release DO is low during high discharges and low discharges occur during the mid-day hours when plant productivity is highest.

The cyclical nature of DO in a tailwater is significantly affected by the mode of operation for hydro generation and must be considered in determining the exposure characteristics of site-specific DO variation to aquatic life. For instance, brief exposures of fish to DO levels as low as 3 mg/L may not be harmful.

Because of the dominant influence of flow and release DO level on downstream DO levels, seasonal variations in these factors are important. High release flow and DO is common in the winter; low flow and high DO is common in the spring during filling of the reservoirs concurrent with cold water temperatures; flows increase with summer power generation and low DO is common in summer and fall due to warmer temperatures of water being released from within the reservoir.

Reaeration. Atmospheric reaeration occurs at the air-water interface and affects dissolved oxygen concentrations throughout the water column by turbulent mixing of surface water to deeper depths. The reaeration rate is usually stated as a product of a reaeration coefficient, K_2 (see Appendix C) and the DO deficit below saturation.

Expressions for the reaeration coefficient have been developed by many investigators where K_2 is directly related to mean velocity and inversely related to mean depth, suggesting a dual effect of an increase in flow on K_2. However, increased depth is more significant than increased velocity so the reaeration rate typically decreases with higher flow in most rivers (see Figure 3-10). Higher flows also reduce the travel times between two river stations, decreasing the opportunity for reaeration as well as the reaeration coefficient.

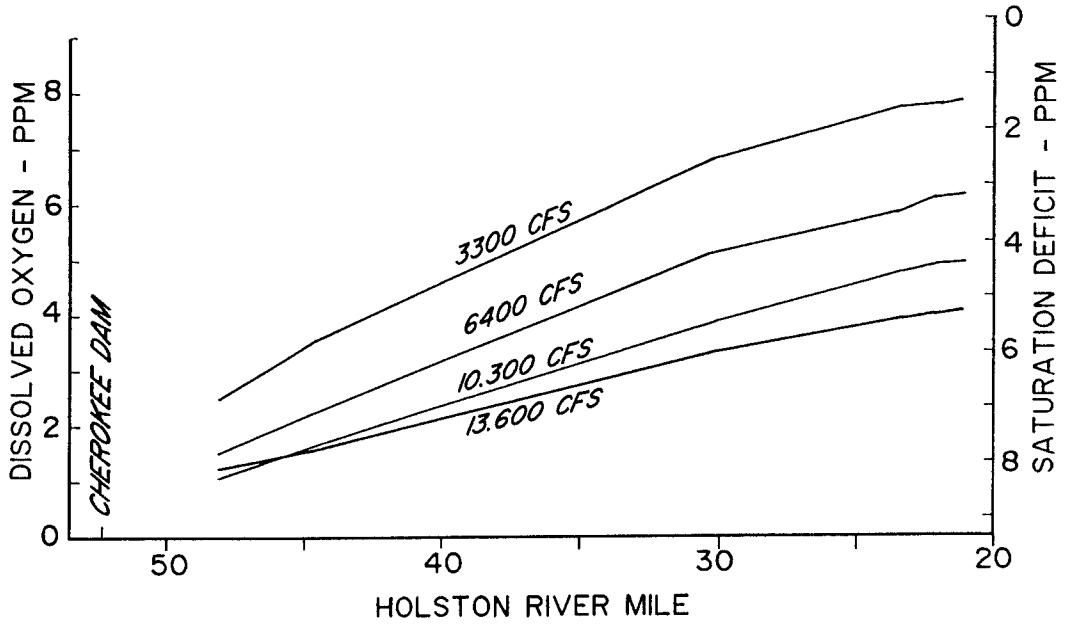


Figure 3-10. Reaeration below Cherokee Dam, showing the effect of discharge on the rate of reaeration in a free-flowing tailwater. Lower flows cause shallower depths and increase the time of travel within the tailwater, resulting in greater opportunity to reaerate in shorter distances downstream. (These data were collected in 1957, before aquatic weeds affected the DO.) (Ref. 3-21).

Steeper channel slopes, especially with shallow depths, increase K_2. Flow into wide, shallow reaches causes more reaeration than flow into narrow, deep reaches. Wind effects are often neglected in river reaeration modeling. However, relatively minor winds (2 to 5 m/s) can increase K_2 considerably, and can even become the dominant factor in long, deep pools with little turbulence, especially during low flow conditions.

Natural reaeration in shallow tailwaters eventually mask downstream DO improvements that result from artificial aeration at an upstream dam. This occurs because deoxygenated water (higher DO deficit) naturally aerates more rapidly than oxygenated water and both approach saturation asymptomatically. Thus, DO improvements at the dam will gradually disappear in the downstream direction, especially at low flows. On the other hand, artificial aeration at a dam with a slow, deep tailwater will have more impact on DO improvement downstream (see Figure 3-11). In the slow, deep tailwater, the DO in the releases from the dam can persist for many miles, dominating the DO in the tailwater more than any other factor.

In most tailwaters, the effect of temperature on the DO saturation deficit is greater than that on the reaeration coefficient, causing the overall reaeration rate to decrease as temperature increases. During periods of high photosynthetic oxygen production, the DO can temporarily supersaturate (DO exceeding saturation) and de-aeration will occur.

Small dams and other hydraulic structures can often contribute modest increments of DO improvement due to reaeration, depending on the head differential, dam shape, and the upstream DO deficit (Ref. 3-21).

Aquatic Vegetation. Aquatic vegetation (algae, macrophytes) contributes oxygen to the water column during photosynthesis and consumes oxygen for respiration. Photosynthesis is roughly confined to the third of the day with the highest solar radiation, while respiration is more evenly distributed throughout the day and night (depending primarily on temperature). Photosynthetic oxygen production can be quite high, normally exceeding respiration demand during this third of the day (except perhaps on overcast days), while respiration

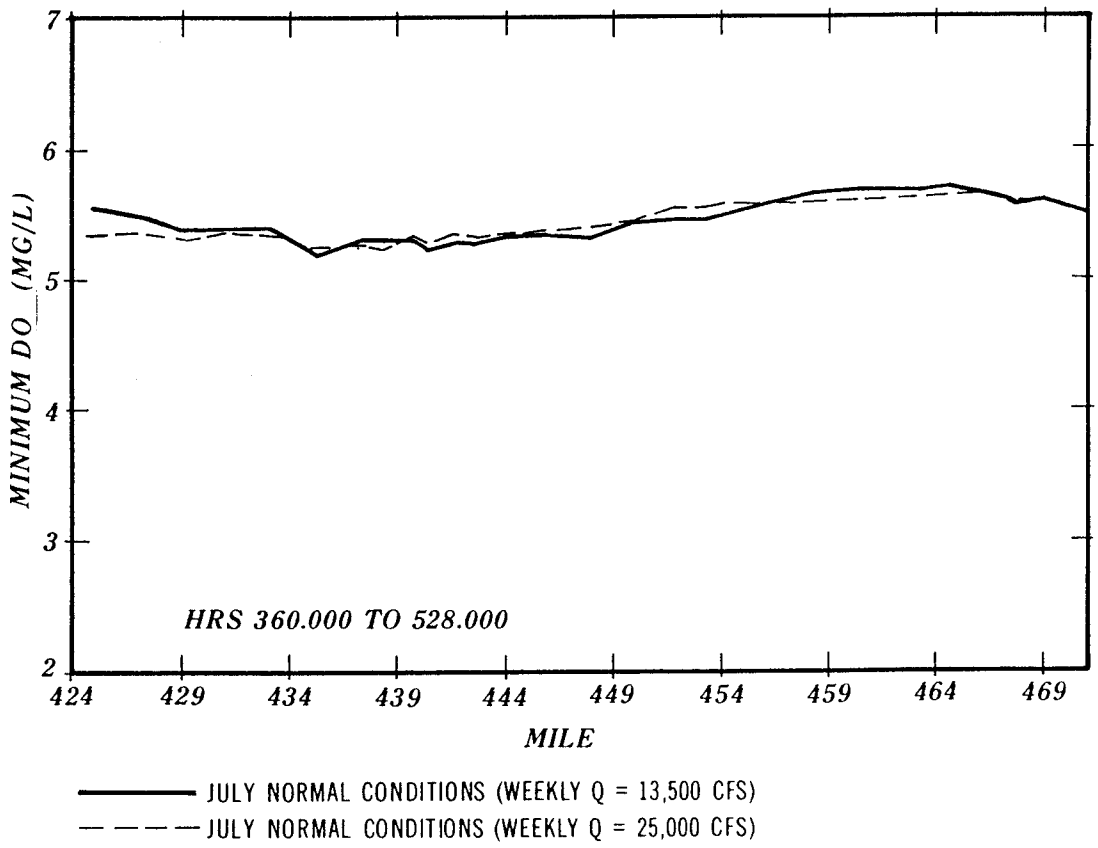


Figure 3-11. Reaeration below Chickamauga Dam, showing the effect of discharge and upstream DO on a pooled tailwater (headwater of Nickajack Reservoir). The rate of DO change is relatively low and even decreases a small amount, and it appears to be insensitive to level of discharge. (Ref. 3-24).

demands prevail at night when there is no photosynthesis. Thus, the aquatic plant community can be a net source of oxygen in daytime hours and a net demand for oxygen at night. Depending on the aquatic plant density, respiration during low flow can create localized reaches of low DO in pre-dawn hours that are lower than the low DO caused by dam releases. Daily average production and demand may vary, but are often in approximate balance with one another in the range of 5 to 10 gm O_2/m^2/day each.

Basic requirements for growth of aquatic plants are light, nutrients (nitrogen, phosphorus, carbon), and suitable temperature. If any of these are limiting or if any toxins are present, plant growth can be limited. Tailwater temperatures are highly variable depending on release temperature, but plant species exist which are well adapted to virtually any tailwater temperature condition.

Daily variations in DO tend to be greater in the shallower depths due to the combined effects of numerous processes on the reduced volume of water. This effect occurs in the transverse direction as well as the longitudinal. Along river banks, for example, daytime DO concentrations are often elevated 0.5 to 1 mg/L (and in some cases 2 mg/L and more) relative to that of the main channel due to combined effects of plants, shallower depths, and slower velocities (longer travel times). Evening DO levels in these areas can be lower by similar amounts compared to that of the main flow.

Sediment Oxygen Demand (SOD). Bacterial decomposition of organic matter (leaf litter, dead bacteriological growths, and dead aquatic plants) in sediments also consumes oxygen from the water column. Another source of organic deposits is particulate matter from wastewater treatment plant discharges. Respiration of the benthic community during decomposition of organic sediments can create significant oxygen demands, especially in pools where organic deposits may be significant and the residence time of water over the sediments is prolonged. Sediment oxygen demand of most river mud falls in the range of 0 to 2 gm $O_2/m^2/day$, but can exceed 10 gm $O_2/m^2/day$ downstream from municipal and industrial discharges.

Water Temperature. Atmospheric heat exchange due to solar and atmospheric radiation and sensible heat transfer is a primary driving force for warming and cooling of releases into tailwaters (especially during low flows), as is release temperature (especially during high flows). Solar radiation also provides energy for plant photosynthesis with associated oxygen production. As discussed earlier, temperature determines both the saturation oxygen concentration and the rates of most physical and biochemical processes affecting DO. The rates of many biochemical processes can double with a 10°C rise in temperature in the range of temperatures found in many tailwaters.

Additional Factors. Many factors specific to certain tailwaters may have important effects on the local oxygen budget. These include such factors as oxidation of reduced chemical elements (iron, sulfide and manganese) in releases; quantity and quality of tributaries; presence of toxic compounds; and respiratory demands of localized heavy concentrations of mussels or other fauna.

Waste Discharges:
Waste discharges commonly impact tailwater DO concentrations in the water column via biochemical oxygen demand of carbonaceous materials and nitrification of ammonia nitrogen. Organic decomposition can involve both dissolved substances that remain in the water column and particulate substances that settle. Waste discharges can also indirectly affect oxygen budgets by contributing dissolved nutrients or waste heat, stimulating growth of aquatic vegetation.

The assimilation capacity of a river is defined as the amount of oxygen-demanding pollutants which can be stabilized without causing the DO to decline below the concentration established by the water quality regulatory agency.

Municipalities and industries are required to treat the oxygen demanding pollutants based on limits which are applicable to various types of wastewaters. However, all of the pollutants cannot be removed and regulatory agencies allocate a certain amount of the assimilative capacity in the receiving body of water for stabilization of the residual pollutants in their discharges.

Regulatory agencies use two broad categories of treatment standards: effluent standards and water quality standards. Effluent standards stipulate the maximum concentration of pollutant allowed in the treated effluent. Water quality standards generally stipulate the minimum DO which will be allowed to exist in the river under certain specified critical conditions. For instance, a state regulatory agency may issue permits for disposal of wastewater from a certain number of industries and municipalities in a river which utilize all of the assimilative capacity available in that reach of river. This situation is termed a water quality limited river. Since assimilative capacity is based upon assumed flow patterns and DO concentra-

tions, significant changes in these caused by a hydropower installation or operation could force the existing dischargers into a water quality violation. In order to get back into compliance, the existing discharges would have to cut production or increase treatment efficiency. Both remedial actions have significant economic implications and, therefore, permitted discharge parties have a keen interest in any changes in river flow pattern or discharge DO from proposed or existing hydropower operations. A hydropower dam operating for peaking power production only 5-days per week can severely impact a downstream reach of river receiving continuous discharge of treated wastewater from a municipality. Installation and operation of a hydropower facility at either an existing or new dam has the potential of altering both flow patterns and DO in the discharge and is therefore subject to intense scrutiny by state regulatory agencies, industries, and municipalities with vested interests in the downstream reach of river.

Typically, in many situations, assimilative capacity can be accommodated in a cost-effective manner, but it is dependent on determining the specific needs for the hydropower releases. The two main variables are the level of DO and the minimum schedule for releases. In the TVA system, the minimum schedule of release can range from a 1-hour pulse release every 4-hour period at Fort Patrick Henry Dam (Ref. 3-22) to an allowable 36 hour shutoff period at Chickamauga Dam (Ref. 3-23). Such determinations can only be made using non-steady state computer models to define the relationships between the hydropower releases, the wastewater discharges, and downstream DO.

Water Supply Considerations:
Municipal and industrial water supplies may be withdrawn downstream of hydropower discharges. DO is usually not the major water quality parameter of interest for water supplies, but very low DO concentrations, particularly in reservoirs, can create problems for drinking water supplies downstream. If iron and manganese are discharged downstream, these compounds can create difficult staining problems in household fixtures or textile processing. Also, hydrogen sulfide causes severe taste and odor problems.

3.4 BIOLOGICAL EFFECTS OF LOW DO LEVELS

Physical Factors Affecting The Magnitude Of Biological Responses

Dissolved oxygen is essential and sometimes the limiting factor for maintaining aquatic life (Ref. 3-24). Depletion of dissolved oxygen is the most biologically important, deleterious water quality impact to many river systems. The degree or severity of biotic effects depends upon the magnitude of DO reduction (including discharge rates, timing, etc., determining exposures), the amount of longitudinal and vertical areas affected, species of fishes and other biota present, their behavior, and their individual sensitivities to lowered concentrations of DO.

If conditions become seasonally anoxic and widespread spatially within a reservoir, there is a loss of available habitat with DO levels acceptable to fishes. Many fish species and life stages sense low DO concentrations and attempt to avoid them by entering shallower shoreline areas, by entering the epilimnion, or moving upstream, downstream or into oxygenated tributaries. This emigration may allow increased predation upon them by other fishes; concentrate them, increasing angler harvest; or put some species in sub-optimal habitat where they are subjected to physiological stresses from higher than acceptable temperatures leading to increased incidence of disease and mortality. Early life stages, such as embryos or larvae developing in nursery areas, are often unable to leave the area and simply die. Lethal DO concentrations result in higher rates of mortality, delayed development and hatching, and smaller hatching sizes. Laboratory investigations suggest those young of some species which do survive exposure to low concentrations of DO during early development, may be weak and suffer significant delayed mortalities.

Seasonally, as temperatures rise, stratification strengthens and DO-depletion progresses, deep-release reservoirs discharge waters of increasingly poorer quality. Biological impacts of low DO are typically localized in the tailwater due to the natural reaeration that eventually occurs downstream. The downstream distances required for reaeration may, however, be quite significant (ranging from 10 to 70 km). Within this area, the severity of biological DO-related impacts are greatest in the near-dam tailwater. Here, the most

severe depression of fish and benthic diversity and/or numbers, occurs. As DO conditions ameliorate downstream, a variable biological "recovery zone" occurs in which benthic and fishery diversity increases and depression of growth or survival of young fish should be attenuated. The extent of this DO-related recovery zone is proportional to the amount of discharge and duration of DO depletion, and is indirectly proportional to the natural stream reaeration rate. Temperature and flow-related recovery zones may also occur, which makes cause-and-effect attribution of impacts solely to low DO concentrations complex, but sometimes not impossible. In addition, turbulence in the near-field zone below a dam can be sufficient to severely limit the growth of benthic organisms need by fish for food supply.

Low DO zones may also act as effective barriers or delays to either upstream passage of fish in spawning migrations, and possibly (not as yet documented) young anadromous fish passing downstream. The severity of a physico-chemical barrier, such as low concentrations of DO, depends upon the magnitude of the DO depression, its longitudinal distance in the river, reservoir or estuary, seasonal timing and duration of the DO-depression, the DO sensitivity of the fish species involved, their species-specific behavior, and DO effects on swimming performance.

Biological Responses To Low Dissolved Oxygen

In many cases, differentiating sublethal DO-related effects from those produced by the many other co-occurring physical, chemical and biological alterations is often difficult in field evaluations. The following impacts, however, are known to occur as consequences of low concentrations of DO in reservoirs and downstream regulated rivers.

Benthos. Benthic organisms (those living on or among the bottom substrate) serve vital functions in the energetics of river systems, transforming nutrients and organic materials into biomass, and providing a food base for fishes and other vertebrate predators. The major effect of low dissolved oxygen on benthic communities is the reduction of species diversity (Ref. 3-25 and Ref. 3-26). Measures of benthic communities in tributary tailwaters of the Tennessee River Valley have been correlated with minimum dissolved oxygen levels

(Ref. 3-27) through the range of 0 to 7 mg/L DO. Crustaceans, freshwater snails, mussels, and aquatic insect larvae show avoidance of low DO or behavioral responses such as suspension of feeding, inactivity, or drifting from affected areas (Ref. 3-28 and Ref. 3-29). Benthic organisms which die or drift from areas to avoid low DO are often replaced by other invertebrate species which can tolerate low DO conditions. Community composition is drastically altered in regulated rivers subjected to low concentrations of DO, but total standing crop (the biomass or total number of organisms present at a specific time) may not change or, actually may increase due to a lack of competition between species. Therefore, benthic communities in DO-altered tailwaters often consist of large numbers of the few species able to live under low DO conditions. Unfortunately, these few tolerant organisms are also most often of poor quality as a food base for fishes or other higher vertebrates.

Freshwater mussels, an important commercial resource in much of the Mississippi River drainage for the cultured pearl-producing industry of the United States and Japan, have been severely reduced by low DO levels within reservoirs and regulated river reaches. Exploitable mussel resources have completely disappeared in many permanent pool areas of tributary and mainstream reservoirs of the United States. This reduction has been the result of multiple stresses including tremendous habitat losses (largely due to impoundment), habitat alterations from sedimentation and pollution, and commercial over-harvest. Mussel distributions also indicate that anoxic conditions in the hypolimnia of reservoirs have played a significant role in regional declines.

Fisheries. Documented detrimental impacts of low dissolved oxygen on fish or fisheries include (Table 3-3): decreased survival (i.e., "fish kills" and increased mortality of embryos, larvae, juveniles and adults); depression of growth rates with consequent impairment of production; decreased reproduction; impaired swimming performance; avoidance behavior of both young and adults leading to denial of access to spawning sites or downstream nursery areas; forcing of adult and juvenile fish into less than optimal habitat conditions; abnormal behavior probably resulting in an increase of fish being preyed upon; decreased fish species diversity; greater synergistic,

Table 3-3

IMPACTS OF BIOLOGICAL IMPORTANCE RESULTING FROM RESERVOIR DO DEPLETION

Within Both The Reservoir And Downstream Regulated River:

- Impaired growth, and increased direct lethality, reducing survival of early life stages (embryos, larvae, alevins) not mobile enough, not able to sense low DO concentrations or requiring higher intergravel concentrations of DO.
- Disruption of upstream spawning migrations by acting as a barrier to fishes not able or willing to pass through areas of low DO to reach spawning grounds.
- Blockage of downstream passage of young of anadromous fishes.
- Behavioral changes induced by low DO stress, which may make young or adult fishes more susceptible to predation.
- Loss of acceptable habitat meeting DO requirements of fish, resulting in emigration of fishes from the entire area to avoid low concentrations of DO.
- Reduction (by direct mortality or by inducing drift) of diverse food supply by eliminating or decreasing numbers of "preferred" bottom-dwelling organisms such as burrowing mayflies in reservoirs or stoneflies in rivers.
- Toxicity (lethal and sublethal) to fishes or benthos from hydrogen sulfide or re-solubilized manganese and iron forming in the anoxic portion of the reservoir and subsequent release to the regulated river.

Within The Reservoir:

- Forcing of adult or juvenile fishes to move into shallower, more well-oxygenated, but possibly thermally stressful areas of the reservoir. This movement may result in reduced survival (fish kills) and/or growth due to physiological stress, predation, disease, or by concentrating fish, making them more susceptible to harvest by anglers.
- Reduction of spatial habitat for spawning by deep water spawners.
- Reduction or loss of deep water nursery areas.

Within The Downstream Regulated River:

- Loss of riffle or shallow riverine spawning and nursery habitat to riverine species sensitive to low DO concentrations
- Fish kills resulting from sudden changes in DO levels in conjunction with other rapidly changing water quality factors resulting from reservoir operations.

toxicity-related mortalities from environmental contaminants under low DO conditions; and increased incidence of disease. The impacts of low DO levels on mortality, growth and fecundity of fishes are similar to those observed for toxic pollutants, i.e., they have a range of impairment effects (toxicities), acute and chronic mechanisms, and affect specific organs, etc.

When not present in lethal concentrations to aquatic life, dissolved oxygen acts as a limiting factor, much as food availability does, setting intermediate sub-lethal limits to growth of fish. Impairments to fishery production (growth, reproduction and survival) can result from less-than-saturated DO concentrations in reservoirs and river reaches in most of the United States. However, neither validated models nor direct production-effects estimates have as yet been developed relating DO levels and fish production under field conditions. Development of national (Ref. 3-30) and regional (Ref. 3-31 and 3-32) DO criteria have been based upon laboratory studies and represent the best available estimates of DO concentrations necessary to protect aquatic life.

Sensitivities of fish to low concentrations of DO vary dramatically between the coldwater salmonids (trout, salmon, char and whitefish) and warmwater or coolwater non-salmonids, by species within these gross characterizations, and by life stage.

As a group, the coldwater salmonids appear to be the most sensitive fishes to low concentrations of DO. Salmonids exhibit slight growth reductions at decreased DO levels above 6 mg/L (<10% impairment); "moderate" reductions (20% impairment) between 4 and 6 mg/L; and "severe" reductions (40% impairment at DO concentrations below 4 mg/L (Ref. 3-30). These impaired growth rates only occur during the period of low DO; therefore, the overall seasonal and annual growth rate may not be evident in field situations. These values are necessarily subjective, but are based upon examination of growth and survival data, generalizations of response curve shape, and assumed applicability of laboratory data to field conditions. With the exception of the smallmouth bass, non-salmonids appear considerably less sensitive to acute effects of low DO than coldwater salmonids.

Early life stages of salmonids do not appear any more susceptible to impacts from low DO than adults, both being more sensitive than warmwater and coolwater non-salmonids. However, embryonic and early life stages of salmonids developing within the interstices of bottom substrate require about 3 mg/L higher DO concentrations in over-passing waters in order to ensure adequate inter-gravel DO concentrations for normal development. Early life stages of non-salmonids species, however, are typically more sensitive to exposure to low DO than juveniles or adults. Significant damage and mortalities have been reported by several authors for young non-salmonids in the 3 to 6 mg/L DO range. Observed effects of low DO on non-salmonids have included delayed development, reduced larval survival, and reduced growth of larvae and juveniles.

Survival data for warm and coolwater fishes show a wide spectrum of relative tolerance to low concentrations of DO. Some species, such as the largemouth bass, white sucker, black crappie and white bass, are relatively tolerant of low DO concentrations, whereas others such as the channel catfish, walleye, northern pike and smallmouth bass are much less tolerant of low DO levels.

Most knowledge of DO-related impairment to fisheries has been gleaned under conditions of constant DO concentrations. However, as described earlier, DO concentrations below hydropower facilities used for "peaking" purposes typically vary drastically with flow over a 24-hour period. The degree of impairment to survival and growth of fishes subjected to cyclical fluctuations in DO, such as occur below these facilities, appears more controlled by the minimum DO concentration to which fish are exposed, rather than daily mean concentrations. Investigations (Ref. 3-33, 3-34, and 3-35) have demonstrated that growth of fish under virtually any fluctuating DO pattern is less than if fish were held at the daily mean DO concentration for the entire period; however, the most recent criteria published by EPA (Ref. 3-30) allows periodic cyclical minimum DO exposures as long as specified minimum DO concentrations are maintained (Table 3-4). TVA data (Ref. 3-36) support the EPA criteria.

Initial research into relative effects of various periods and cyclical variation in timing of exposure to low DO concentrations have

Table 3-4

EPA WATER QUALITY CRITERIA FOR AMBIENT
DISSOLVED OXYGEN CONCENTRATIONS

	Coldwater Criteria		Warmwater Criteria	
	Early Life Stages[1,2]	Other Life Stages	Early Life Stages[2]	Other Life Stages
30 Day Mean	NA[3]	6.5	NA	5.5
7 Day Mean	9.5 (6.5)	NA	6.0	NA
7 Day Mean Minimum	NA	5.0	NA	4.0
1 Day Minimum [4,5]	8.0 (5.0)	4.0	5.0	3.0

1 These are water column concentrations recommended to achieve the required intergravel dissolved oxygen concentrations shown in parentheses. The 3 mg/l differential is discussed in the criteria document. For species that have early life stages exposed directly to the water column, the figures in parentheses apply.

2 Includes all embryonic and larval stages and all juvenile forms to 30-days following hatching.

3 NA (not applicable).

4 For highly manipulatable discharges, further restrictions apply (see page 37 of the EPA Criteria Document) For the 1 day minimum for other life stages, it was recommended that the criteria be increased by 0.5 mg/L.

5 All minima should be considered as instantaneous concentrations to be achieved at all times.

(Ref. 3-30)

indicated that some diurnal fluctuation regimes are less detrimental to fish than others. Further research along this avenue would yield site-specific alternatives for operational schemes at hydroelectric facilities that would mitigate aquatic biological impacts, while minimizing energy or operational costs and losses to power producers.

For a more comprehensive discussion on fishery considerations, see Section 5.

Section 4

AGENCY INVOLVEMENT

The following material is presented as an aid to understanding how the various agencies became involved in the subject of dissolved oxygen. By reviewing the historical development, a better perception of the agencies' goals should result. This understanding should aid those readers throughout the consultation process.

4.1 HISTORICAL PERSPECTIVE

Although not a substance capable of degrading water quality, dissolved oxygen historically has been of interest in water quality investigations. It generally has been considered significant in the protection of aesthetic qualities of water as well as for the maintenance of fish and other aquatic life. Dissolved oxygen concentrations are an important gauge of existing water quality and the ability of a water body to support a well balanced aquatic fauna (Ref. 4-1).

Studies of the effects of pollutants on water quality began in the early 1900s. Specific federal legislation for water quality was first enacted in 1948 with passage of the original Federal Water Pollution Control Act and was strengthened in 1965 with passage of the Water Quality Act. These acts have been supplemented since that time by many additional acts and amendments thereto. The basic applicable federal legislation presently in effect is the Clean Water Act, originally enacted as the Federal Water Pollution Control Act of 1972, and extensively amended since that time.

Hydropower Licensing Before the National Environmental Policy Act

Prior to the late 1960s, the Federal Power Commission (FPC) (changed to the Federal Energy Regulatory Commission in 1977), in accordance with the Fish and Wildlife Coordination Act of 1958, was required to consult with the U.S. Fish and Wildlife Service (USFWS) and the state

natural resources agencies, but environmental concerns were not given great importance in the licensing process. These agencies provided written comments back to FPC on the environmental aspects of license applications, but license requirements rarely were more specific than that the licensee should consult with the USFWS and applicable state agencies.

In 1969, the FPC strengthened the environmental aspects of its licensing rules by requiring an applicant to furnish information on a range of environmental considerations, including preparation of Exhibits R, S, and V. Under Exhibit R, the applicant was required to submit a plan for the development of the project's recreational resources. Exhibit V required the applicant to provide information on the natural, historic, and scenic values and resources of the project area.

Under Exhibit S, the applicant was required to submit "a report on the effect, if any, of the project upon the fish and wildlife resources in the project area or in other areas affected by the project and proposals for measures considered necessary to conserve and, if practicable, to enhance fish and wildlife resources affected by the project" (Ref. 4-2). Indirectly, at least, serious dissolved oxygen questions were to be addressed in Exhibit S because of their potential for adverse effects on fishery resources. Exhibit S further strengthened the requirement for coordination and consultation with the USFWS and state conservation agencies.

Requirements of the National Environmental Policy Act and the Environmental Protection Agency

Significant procedural changes in consideration of the environment during project licensing (and relicensing) resulted from enactment of the National Environmental Policy Act of 1969 (commonly called NEPA). Among other provisions, NEPA directs agencies of the Federal Government to develop procedures "which will insure that presently unquantified environmental amenities and values may be given appropriate consideration in the decision-making along with economic and technical considerations" and requires that all agencies of the Federal Government prepare a detailed statement concerning Federal actions "significantly affecting the quality of the human environment."

In accordance with regulations implementing NEPA, the FPC issued an order (Ref. 4-3) in December 1970 that required applicants to prepare an Exhibit W which was a statement of environmental factors as specified by NEPA. In 1978, FERC further revised their regulations for license applications and consideration of environmental questions by combining and expanding the information requirements of Exhibits R, S, V, and W into a new Exhibit E.

One aspect of the environmental movement of the 1960s and 1970s was specific concern for water quality and the development of specific water quality criteria and standards. The Federal Water Pollution Control Act, as amended by the Water Quality Act of 1965, authorized the States and the Federal Government to establish water quality standards for interstate (including coastal) waters. In terms of water quality, the terms "criteria" and "standards" have specific meaning and should not be used interchangeably.

> A "criterion" "represents a constituent (in this case dissolved oxygen) concentration or level associated with a degree or environmental effect upon which scientific judgement may be based. As it is currently associated with the water environment, it has come to mean a designated concentration of a constituent that, when not exceeded, will protect an organism, an organism community, or a prescribed water use or quality with an adequate degree of safety". For dissolved oxygen, it is the minimum concentration that is of concern.
>
> "On the other hand, a standard connotes a legal entity for a particular reach of waterway or for an effluent. A water quality standard may use a water quality criterion as a basis for regulation or enforcement, but the standard may differ from a criterion because of prevailing local natural conditions..." (Ref. 4-1).

Pursuant to the Water Quality Act of 1965, the first National Technical Advisory Committee on Water Quality Criteria prepared a report, Water Quality Criteria, in April 1968. Under the heading Dissolved Oxygen, the following criteria were presented:

> "(1) For a diversified warm-water biota, including game fish, DO concentration should be above 5 mg/L, assuming normal seasonal and daily variations are above this concentration. Under extreme conditions, however, they may range between 5 and 4 mg/L for short periods during any 24-hour period, provided that the water quality is favorable in all

other aspects. In stratified lakes, the DO requirements may not apply to the hypolimnion. In shallow unstratified lakes, they should apply to the entire circulation water mass.

"These requirements should apply to all waters except administratively established mixing zones. In lakes, such zones must be restricted so as to limit the effect on the biota. In streams, there must be adequate and safe passageways for migrating forms. These must be extensive enough so that the majority of plankton and other drifting organisms are protected.

"(2) For the cold-water biota, it is desirable that DO concentrations be at or near saturation. This is especially important in spawning areas where DO levels must not be below 7 mg/L at any time. For good growth and the general well-being of trout, salmon, and their associated biota, DO concentrations should not be below 6 mg/L. Under extreme conditions, they may range between 6 and 5 mg/L for short periods provided the water quality is favorable in all other respects and normal daily and seasonal fluctuations occur. In large streams that have some stratification or that serve principally as migratory routes, DO levels may range between 4 and 5 mg/L for periods up to 6 hours, but should never be below 4 mg/L at any time or place."

The Federal Water Pollution Control Act of 1972 required the Administrator of the Environmental Protection Agency (USEPA) to publish "criteria for water quality accurately reflecting the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare..." A report, "Quality Criteria for Water" was prepared and released in final form in July 1976. The thrust of the report was "to recommend criteria levels for a water quality that will provide for the protection and propagation of fish and other aquatic life and for recreation in and on the water." Again, these criteria would be used to formulate state water quality standards that would have to be met in order to qualify for discharge permits.

The dissolved oxygen criteria presented in that report for freshwater aquatic life were:

"A minimum concentration of dissolved oxygen to maintain good fish populations is 5.0 mg/Liter.

"The criterion for salmonid spawning beds is a minimum of 5.0 mg/Liter in the interstitial water of the gravel."

The most recent, generally recognized criteria for dissolved oxygen were published by USEPA in April 1986. These criteria "represent the best estimates, based on the data available, of dissolved oxygen concentrations necessary to protect aquatic life and its uses." A warm water/cold water dichotomy was made in this criterion, as in the previous versions.

Table 4-1 presents the currently recognized ambient dissolved oxygen concentrations necessary for the protection of freshwater aquatic life. These criteria are derived from biotic production impairment estimates

> "which are in turn based primarily upon growth data and information on temperature, disease, and pollutant stresses. The average dissolved oxygen concentrations selected are values 0.5 mg/L above the slight production impairment values and represent values between no production impairment and slight production impairment. Each criterion may thus be viewed as an estimate of the threshold concentration below which detrimental effects are expected.
>
> "Criteria for cold water fish are intended to apply to waters containing a population of one or more species in the family Salmonidae or to waters containing other cold water or cool water fish deemed by the user to be closer to salmonoids in sensitivity than to most warm water species... Many states have more stringent dissolved oxygen standards for cooler waters, waters that contain either salmonids, non-salmonid cool water fish, or the sensitive centrarchid, the smallmouth bass. The warm water criteria are necessary to protect early life stages of warm water fish as sensitive as channel catfish and to protect other life stages of fish as sensitive as largemouth bass. Criteria for early life stages are intended to apply only where and when these stages occur. These criteria represent dissolved oxygen concentrations which USEPA believes provide a reasonable and adequate degree of protection for freshwater aquatic life." (Ref. 4-4, p. 33).
>
> "The previous USEPA criterion for dissolved oxygen published in Quality Criteria for Water (Ref. 4-1) was a minimum of 5 mg/L (usually applied as a 7Q10) which is similar to the current criterion minimum except for other life stages of warm water fish which now allows a 7-day mean minimum of 4 mg/L. The new criteria are similar to those contained in the 1968 "Green Book" of the Federal Water Pollution Control Federation (Ref. 4-5)." (Ref. 4-4, p. 36).

These criteria will weigh heavily in determining minimum dissolved oxygen concentrations as states review or revise their standards.

Table 4-1

WATER QUALITY CRITERIA FOR AMBIENT DISSOLVED OXYGEN CONCENTRATION

	Coldwater Criteria		Warmwater Criteria	
	Early Life Stages[1,2]	Other Life Stages	Early Life Stages[2]	Other Life Stages
30-Day Mean	NA[3]	6.5	NA	5.5
7-Day Mean	9.5 (6.5)	NA	6.0	NA
7-Day Mean Minimum	NA	5.0	NA	4.0
1-Day Minimum[4,5]	8.0 (5.0)	4.0	5.0	3.0

1. These are water column concentrations recommended to achieve the required intergravel dissolved oxygen concentrations shown in parentheses. The 3 mg/L differential is discussed in the criteria document. For species that have early life stages exposed directly to the water column, the figures in parentheses apply.

2. Includes all embryonic and larval stages and all juvenile forms to 30-days following hatching.

3. NA (Not Applicable)

4. For highly manipulative discharges, further restrictions apply (Ref. 4-4, p.37).

5. All minima should be considered as instantaneous concentrations to be achieved at all times.

(Ref. 4-4)

Hydropower Licensing After NEPA

There was relatively little licensing activity in the early 1970s as applicants assessed the implications of the new requirements for their projects and prepared their license applications. Water quality concerns in general were addressed by both applicants and FERC (FPC), but dissolved oxygen was generally not treated specifically unless a special concern was recognized. During the mid- to latter part of the 1970s, requirements for extensive pre- and post-operational monitoring were incorporated into hydropower licensing

and the Commission reserved "the right, after notice and opportunity for hearing, to require additional studies and to require such reasonable changes in the project and its operation as may be found necessary or appropriate to maintain or improve the aquatic environment."

Article 43 of the 1977 Ordering Opinion for the Bath County Pumped Storage Project (Project No. 2716) was typical of such requirements (Ref. 4-6). The Opinion cited that the Virginia Electric and Power Company had "studied the quality of the water in the project area, including its chemical properties and temperature range" and that post-operational water quality monitoring programs had been approved by the Virginia State Water Control Board. Water quality was noted as being "good". Temperature and the potential for stratification were specifically addressed, but not dissolved oxygen. It was concluded that the project "will likely have no adverse impact on the fish species" downstream of the project. These studies were instituted at the request of the state, rather than FPC. Generally, however, detailed analyses of likely project impacts on water quality were not required prior to issuance of the license.

Among the first specific stipulations in license articles regarding dissolved oxygen were those of 1980 for four projects on the lower Susquehanna River that were undergoing relicensing. These projects were:

FERC Project No. 0405, Conowingo Project
No. 1881, Holtwood Project
No. 1888, York Haven Project
No. 1025, Safe Harbor Project

Virtually identical license articles for these projects stipulated that the

> "Licensee shall, in consultation with the Pennsylvania Fish Commission, the U.S. Fish and Wildlife Service of the Department of the Interior, and the Susquehanna River Basin Commission, develop a mutually satisfactory study plan to determine: (1) the seasonal variations of dissolved oxygen concentration and temperature in the project reservoir and in the discharge from the project; (2) the effects of project operation on temperature and dissolved oxygen levels in the

reservoir and discharge from the project; (3) the source, nature, and quantity of oxygen-demanding materials present in and entering the project reservoir; (4) the most feasible methods for ensuring that water released from the project meets state water quality standards; and (5) the minimum flow releases from the project that are necessary to protect and enhance fish and wildlife resources. The development of the plan shall be coordinated with the coincident study plans of dissolved oxygen conditions and flow releases being developed for the Conowingo Project (FERC No. 405), the Safe Harbor Project (FERC No. 1025), and the Holtwood Project (FERC No. 1881), and shall include consideration of the operation of other headwater developments in the basin. Within 4 months from the date of issuance of this license, the Licensee shall file for Commission approval a mutually satisfactory study plan. If the Licensee and the agencies consulted cannot agree on a study plan, then within 4 months from the date of issuance of this license the Licensee shall file its proposed study plan with the Commission for approval, together with any reports or comments it has received on the plan from any consulted agency. At the same time, copies of the filing shall be served upon the agencies consulted. The Commission reserves the right to require modifications to the study plan.

"The Licensee shall conduct the study as approved by the Commission. Within 3 months after the date of completion of the study, the Licensee shall file with the Commission for approval a report on the results of the study, including a schedule of minimum flow releases from the project and recommended measures for the maintenance of state water quality standards. At the same time, copies of the report shall be served upon the agencies consulted."

(Article 39 of License issued to York Haven Power Co., August 14, 1980, for the York Haven Project, No. 1888.)

These stipulations were the outgrowth of concerns, initially expressed by the Maryland Department of Natural Resources, and the Maryland Department of Health and Mental Hygiene, regarding water quality and the survival of anadromous fish downstream of the Conowingo Project.

Similar requirements for the development of plans for meeting state water quality standards based on post licensing studies were commonly included in project licenses during the early 1980s.

This practice was changed in 1984 by the Yakima decision in which the courts affirmed that an analysis of likely project impacts needed to be completed and included in an environmental impact statement for the project **prior** to issuance of the license. As a result of that

decision, preliminary evaluations of expected project impacts on water quality were made prior to licensing and, therefore, license articles became more specific as to monitoring requirements and remedial actions. For example, Article 20 of the license issued to the City of Jersey City for Project Number 5989 (July 18, 1985) stipulated that the

> "Licensee ..., shall develop a detailed plan to ensure that the discharge of the proposed project complies with State water quality standards for dissolved oxygen, water temperature and other variables. The plan shall include, but shall not be limited to: an assessment of capability of the turbine venting system for re-aerating the project discharge; specific criteria for project operation and for the release of the minimum flow required by Article 19; facilities to continuously monitor dissolved oxygen and water temperature immediately downstream of the project discharge; and a schedule for providing the monitoring data to the aforementioned agencies.
>
> "Licensee, within 4 months from the date of issuance of this license, shall provide the plan to the Director, Office of Hydropower Licensing. Comments from the aforementioned agencies on the plan shall be included in the filing. The Director reserves the right to require modifications to the plan."

Hydropower Licensing After the Electric Consumers Protection Act

The trend towards more stringent requirements for monitoring and implementation of modifications of project structures or operations has continued following passage of the Electric Consumers Protection Act of 1986 (ECPA) in October 1986. ECPA provided the first legislative change in the Federal Power Act (FPA) since 1935. Passage of ECPA has influenced the licensing process in terms of how fishery issues, including dissolved oxygen concerns, are treated in the licensing process.

Section 4(e) of the FPA, 16 U.S.C. § 797(e), in a provision added by Section 3(a) of the Electric Consumers Protection Act of 1986 (ECPA), Pub. L. No. 99-495 (Oct. 16, 1986), provides that:

> In deciding whether to issue any license under this Part for any project, the Commission, in addition to the power and development purposes for which licenses are issued, shall give equal consideration to the purposes of energy conservation, the protection, mitigation of damage to, and enhance-

ment of, fish and wildlife (including related spawning grounds and habitat), the protection of recreational opportunities, and the preservation of other aspects of environmental quality.

In addition, Section 10(a)(1) of the FPA, as amended by Section 3 of ECPA (provisions added by ECPA indicated in brackets), provides:

> That the project adopted, including the maps, plans, and specifications, shall be such as in the judgment of the Commission will be best adapted to a comprehensive plan for improving or developing a waterway or waterways for the use or benefit of interstate or foreign commerce, for the improvement and utilization of water power development, [for the adequate protection, mitigation, and enhancement of fish and wildlife (including related spawning grounds and habitat),] and for other beneficial public uses, including [irrigation, flood control, water supply, and] recreational and other purposes referred to in Section 4(e) of the FPA; and if necessary, in order to secure such plan the Commission shall have the authority to require the modification of any project and of the plans and specifications of the project works before approval.

Under ECPA, the review and incorporation of the recommendations of the federal and state fish and wildlife agencies are subject to a more formalized process, referred to as the "10(j) process". Section 10(j) of the Federal Power Act reads as follows:

> "(1) That in order to adequately and equitably protect, mitigate damages to, and enhance, fish and wildlife (including related spawning grounds and habitat) affected by the development, operation, and management of the project, each license issued under this Part shall include conditions for such protection, mitigation, and enhancement. Subject to paragraph (2), such conditions shall be based on recommendations received pursuant to the Fish and Wildlife Coordination Act (16 U.S.C. 661 et seq.) from the National Marine Fisheries Service, the United States Fish and Wildlife Service, and State fish and wildlife agencies.
>
> "(2) Whenever the Commission believes that any recommendation referred to in paragraph (1) may be inconsistent with the purposes and requirements of this Part or other applicable law, the Commission and the agencies referred to in paragraph (1) shall attempt to resolve any such inconsistency, giving due weight to the recommendations, expertise, and statutory responsibilities of such agencies. If, after such attempt, the Commission does not adopt in whole or in part a recommendation of any such agency, the Commission shall publish each of the

following findings (together with a statement of the basis for each of the findings):

"(A) A finding that adoption of such recommendation is inconsistent with the purposes and requirements of this Part or with other applicable provisions of law.

"(B) A finding that the conditions selected by the Commission comply with the requirements of paragraph (1)."

A new section, "SEC. 31 ENFORCEMENT" is added to the end of Part I of the Federal Power Act.

"(a) Monitoring and Investigation. The Commission shall monitor and investigate compliance with each license and permit issued under this Part and with each exemption granted from any requirement of this Part. The Commission shall conduct such investigations as may be necessary and proper in accordance with this Act. After notice and opportunity for public hearing, the Commission may issue such orders as necessary to required compliance with the terms and conditions of licenses and permits issued under this Part and with the terms and conditions of exemptions granted from any requirement of this Part."

In accordance with the requirements for monitoring the applicant's compliance with license terms and conditions, a recent review by FERC staff of project licenses issued between July 1986 and December 1988 showed that many contained requirements regarding dissolved oxygen concentrations. A typical minimal requirement contains four parts.

The licensee, after consultation with the U.S. Fish and Wildlife Service and the applicable state fish and wildlife agencies, shall develop a dissolved oxygen (DO) monitoring plan.

The plan shall include measures necessary to effect rapid alteration of project operation to ensure maintenance of the state dissolved oxygen standard.

The plan shall be filed with the Commission for approval within (variable, six months to one year) from the date of issuance of the license.

Documentation of agency consultation and agency comments on the plan shall be included in the filing.

Depending on specifics of the project, these basic requirements may be expanded to include other pertinent state and federal (e.g., USEPA, Corps of Engineers) agencies to be contacted, to specify both pre- and post-construction monitoring, or to include project shutdown as a means of ensuring maintenance of state standards.

Many licenses contained more specific requirements as to what should be included in the monitoring plan. Such requirements include:

> A description of the monitoring system that would be used, including the locations at which the equipment would be positioned.
>
> Plans and timetable for installation, calibration procedures, and reporting requirements.
>
> Stipulated seasonal minimum DO concentrations to be maintained downstream.
>
> Requirements for immediate installation of an aeration system and provision of operating procedures and functional design drawings of the aeration facilities.
>
> Evaluation of the existing aeration effect of the project dam.
>
> Prohibition of project construction until after the dissolved oxygen monitoring plan is submitted and approved by the Commission.

An example of a license requirement specifying in detail the contents of the monitoring plan is Article 402 of the license issued on February 26, 1988 to Clearwater Hydro Associates to construct, operate and maintain the Village Creek Hydro Project in Alabama (FERC Project no. 9876). This project would be constructed at the base of an existing dam and would be operated in an instantaneous, run-of-river mode. During the summer, the reservoir is stratified with DO concentrations ranging from 5.0 mg/L at the surface to 0 mg/L in the hypolimnion.

Article 402 states:

> "The licensee, in cooperation with the Alabama Department of Environmental Management (ADEM), shall develop a plan to ensure that operation of the proposed Village Creek Hydroelectric Project does not cause violation of state water quality standards. Within 6 months of the issuance date of

this license, the licensee shall file with the Commission for approval a plan that includes: (1) a description of the monitoring system that would be utilized to measure dissolved oxygen (DO) concentrations downstream of the project; (2) the distance from the dam at which the equipment that would continuously monitor DO concentrations would be positioned; (3) a schedule for monitoring downstream DO concentrations; (4) a description of operational procedures and aeration equipment that would be used to ensure that project operation does not reduce downstream DO concentrations to levels that are less than the state's standard; and (5) the methods that the licensee would employ to transmit the DO monitoring data to ADEM. The filing shall include comments from ADEM regarding the plan and monitoring program. The Commission reserves the right to require changes to the plan.

"If at anytime, the monitoring program indicates that project operation reduces downstream DO concentrations to levels below the state's standard, the licensee shall immediately implement whatever measures are necessary, including project shutdown, to comply with the state standard. In addition, the licensee shall immediately notify ADEM and the Commission's Atlanta Regional Office that violation of the DO standard resulted from project operation. Further, within 2 months of the violation, the licensee shall file with the Commission for approval a description of changes to project structures or operation that are needed to maintain the state DO standard and a schedule for implementing those changes. Comments from ADEM regarding those proposed changes shall be included in the filing."

Other typical license articles addressing dissolved oxygen monitoring plans, and a more general discussion of the contents of a good monitoring program is contained in Section 7.2.

Specific Agency Consultation Requirements

In March 1985, FERC issued specific requirements for agency consultation during the licensing process. These requirements apply to any license application, including application for relicensing[1], and would include specific consideration of dissolved oxygen questions. The requirements, as subsequently revised to incorporate changes required by ECPA (see 18 CFR Section 4.38), specify that

"(a) An applicant for a license or exemption from licensing must consult with each appropriate Federal and state agency before submitting its application to the Commission. The

[1]On May 17, 1989, FERC issued Order No. 515, implementing revised regulations governing the relicensing of hydroelectric projects.

agencies to be consulted must include the appropriate certifying agency under section 401 of the Federal Water Pollution Control Act (Clean Water Act), 33 U.S.C. 1341..."

A three stage consultation process is required.

"(1) **Initial stage of consultation.** A potential applicant must contact all appropriate agencies and provide each of them with the following information:

(i) Detailed maps with proper land descriptions of the entire project area by township, range and section as well as by state, county, river, river mile, and the closest town. Show the specific location of all proposed project facilities, including roads, transmission lines, and any other appurtenant facilities;

(ii) A general engineering design of the proposed project with a description of any proposed diversion of a stream through a canal or a penstock;

(iii) A summary of the proposed operational mode of the project;

(iv) Identification of the environment to be affected and the significant resources present, and the applicant's environmental protection, mitigation, and enhancement plans to the extent known at that time; and

(v) Streamflow and water regime information, including drainage area, natural flow periodically, monthly flow rates and durations, mean flow figures illustrating the mean daily streamflow curve for each month of the year at the proposed point of diversion or impoundment with location of the stream gauging station, the method used to generate the streamflow data provided, and copies of all records used to derive the flow data used in the applicant's engineering calculations.

(2) **Second stage of consultation.** A potential applicant must perform any reasonable studies that are necessary for the Commission to make an informed decision regarding the merits of the application.

(i) Studies must be conducted prior to filing an application if the results:

(A) Would influence the economic feasibility of the project (e.g., minimum flow study);

(B) Would influence the technical feasibility of the project (e.g., study of potential mass soil movement);

(C) Are needed to determine the design or location of project features;

(D) Are needed to determine the impacts of the project on important natural or cultural resources (e.g., resource surveys);

(E) Are necessary to determine suitable mitigation (e.g., resource surveys);

(F) Are necessary to minimize impacts to a significant resource (e.g., wild and scenic river, anadromous fish, endangered species, caribou migration routes).

(ii) Studies may be conducted after a license or exemption is issued if the studies:

(A) Can be conducted only after the project is operating (e.g., turbine-related fish mortality studies);

(B) Would determine the success of mitigative measures (e.g., post-construction monitoring studies); and

(C) Would be used to refine project operation or modify project facilities.

(iii) A potential applicant must provide each agency with a copy of its draft application, the results of all studies and a written request for review and comment. The draft application must clearly indicate the type of application the applicant expects to file with the Commission...

(3) **Third stage of consultation.** When an applicant files an application with the Commission for an exemption, minor license, or major license less than 5 MW, it must serve a copy of its application upon each of the agencies consulted. An applicant for a major license for 5 MW or more must provide applications to the agencies after receiving noti-

fication by the Commission that the application has been accepted. When an applicant revises, supplements, or amends an application on file with the Commission, or corrects deficiencies in its application pursuant to § 4.32(d)(1), the applicant must serve a copy of the revision, supplement, or amendment upon each consulted agency upon which it had served a copy of the original application.

(c) An applicant must document to the Commission in Exhibit E of its application that the requirements of all three stages of the consultation process have been fully satisfied and must include:

(1) Any agency letters containing comments, recommendations, and proposed terms and conditions; and

(2) With regard to certification requirements for license applicants under section 401 of the Federal Water Pollution Control Act (Clean Water Act), the following:

(i) A copy of the water quality certification, or

(ii A copy of the request for certification, including proof of the date that the certifying agency received the request in accordance with applicable law governing filings with that agency.

(d) If an agency fails to comment in writing within the prescribed time period or fails to otherwise consult, an applicant may describe in detail in Exhibit E of its application all attempts to consult with that agency, the results of any partial consultations that did occur, and any recommendations that the agency did make.

(e) (1) If all the appropriate agencies waive compliance with any requirement of this section, or are deemed by the Commission to have waived compliance under this section, the applicant may omit compliance with that requirement. Except for waiver of water quality certification under paragraph (e)(2) of this section, the applicant must describe in Exhibit E of its application the circumstances of any waiver under this section.

(2) A certifying agency is deemed to have waived the certification requirements of section 401(a)(1) of the Federal Water Pollution Control Act (Clean Water Act) if the certifying agency has not denied or granted certification by one year after the date the certifying agency received the request for certification.

(3) Any material amendment to plans of development proposed in an application for license, as defined under §4.35(b), must be considered to require a new request for certification for the purposes of paragraph (2).

(f) An applicant must identify and explain in the application how and why the project would, or would not, comply with the relevant comprehensive state and regional water resource development plans and programs (e.g., the Columbia Basin Fish and Wildlife Program and the Northwest Power Planning Council Regional Energy Plan). If the project would not comply, the applicant must explain why the project should be allowed to not comply with these plans and programs.

[Order 413, 50 FR 11683, Mar. 25, 1985, as amended by Order 464, 52 FR 5449, Feb. 23, 1987; Order 487, 52 FR 48404, Dec. 22 1987]"

These requirements are presently applicable to all new projects, existing projects that were not previously licensed, and projects up for relicensing (essentially new licenses). They clearly specify that water quality (including dissolved oxygen) issues must be addressed in the license application. FERC will then utilize that information, together with agency comments and recommendations and the analyses of the FERC staff in evaluating likely projects and in determining conditions to be included in any license that may be issued.

4.2 CURRENT TRENDS AND UNRESOLVED CONTROVERSY

This section identifies and discusses areas of concern that are currently subject to controversy and differences of opinion among

agencies. Future handling of dissolved oxygen questions will depend, in part, on how these questions are ultimately resolved.

Basic questions that need to be resolved include:

> What concentrations of dissolved oxygen should be maintained for the protection of aquatic resources?
>
> What constitutes an adequate data base for impact evaluation?
>
> What constitutes adequate evaluation of cumulative impacts?
>
> What constitutes equal consideration of environmental values in project evaluation in accordance with ECPA?

All of these questions are exemplified by the controversy surrounding the FERC document "Environmental Impact Statement: Hydroelectric Development in the Upper Ohio River Basin -- Ohio, Pennsylvania, West Virginia -- FERC Docket No. EL85-19-114." The draft EIS, issued in May 1988, evaluated the cumulative impacts of 24 applications for new hydroelectric projects (including competing applications at five sites) at 19 existing dams in the upper Ohio River basin.[2]

Four hydroelectric generation alternatives, as well as a non-hydroelectric alternative consisting of a 400-megawatt coal-fired power plant, were evaluated to determine the environmental effects and economic benefits. In addition, five dams with no pending license applications and six dams where hydropower licenses have been issued were also evaluated in the water quality modeling portion of the FEIS because they have important interactions with the proposed hydropower

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[2] Subsequent to preparation of the following discussion, FERC issued orders licensing projects at 16 sites and denying license applications for projects at three sites. The order issued September 27, 1989, denying the applications for license, Project Nos. 2971-002, (Allegheny Electric Cooperative), et. al., 48 FERC 61,... (1989), presents a thorough review of the controversy surrounding hydro-development at the sites. The state and federal resource agencies (U.S. Department of the Interior, Pennsylvania Fish Commission, West Virginia DNR, and Ohio DNR) have subsequently filed petitions for rehearings on procedural grounds. The Commission is presently considering these requests. Petitions filed by the agencies for stays of the licenses and requests to file briefs on the issues have been denied by the Commission. The following discussion summarizes the positions taken by FERC and the resource agencies throughout the proceedings.

projects. The cumulative and site specific impacts of the projects were evaluated, taking into account the potential for mitigating adverse impacts. The Scope and Executive Summary of the FEIS are attached as Appendix E of this report. The summary reviews the alternatives evaluated and the reasons for selection of a preferred alternative.

The draft EIS elicited strong adverse comments from the USFWS, the U.S. Environmental Protection Agency, and the state resource agencies. The reactions of these agencies can be summed up by the following excerpt from a USFWS letter dated July 27, 1988.

> "Our review of the DEIS leads us to conclude that the Service is not able to support many of the analyses and conclusions contained in the document. The Service requests that the DEIS be revised and recirculated and suggests changes to protect and develop fish and wildlife resources in the basin."

A copy of the letter, as well as copies of all comment letters on the DEIS, is reproduced in the FEIS issued in September 1988, along with detailed point-by-point responses by the FERC staff. As indicated in the FEIS responses, many of the requests and suggestions put forth by the resource agencies were not accepted by the FERC staff. These areas of difference are discussed in the following sections because they illustrate potential problem areas for applicants for FERC licenses.

Desireable DO Concentrations

One of basic differences of opinion between the FERC staff and the resource agencies concerns the minimum level of dissolved oxygen concentration that should be maintained in the river.

FERC recognized that licensing multiple hydroelectric projects in the upper Ohio River Basin would involve trade-offs between new energy production and environmental quality. Four alternatives were modeled and discussed in the FEIS. These were:

1) Develop the Projects as Proposed. In the case of competing applications, the project with the greater impact on dissolved oxygen concentrations was modeled as a worst case scenario.

2) Project Operation to Meet Dissolved Oxygen Standards. This alternative would require modified flow regulation at proposed projects to provide greater aeration by increased spilling and thus avoid violations of the states' DO standard of 5 mg/L. Only aeration via spillage was considered. Mechanical aeration was deemed to be unproven at these low-head projects.

3) Project Operation to Avoid Degradation of Water Quality that Would Affect Aquatic Life. The objective of this alternative was to operate the projects in such a way that hydropower operations would not cause DO concentrations to fall below 6.5 mg/L anywhere in the rivers where DO concentrations are affected by the projects.

4) Projects Selected to Minimize Impacts to All Target Resources. This alternative would provide the same protection to aquatic resources as Alternative 3, but would also reduce impacts on wetlands, recreation, and fish populations. Three sites would not be developed under this alternative.

The resource agencies strongly recommended that another alternative be modeled: operation of the projects to maintain existing, preproject, dissolved oxygen concentrations in the rivers so that the reaches where DO concentrations are greater than 6.5 mg/L would be maintained at that higher level.

The following paragraphs summarize the arguments put forth by FERC and the agencies concerning what concentrations of dissolved oxygen should be maintained for the protection of aquatic resources.

State Standards Versus Antidegradation Criteria. The states' standard for all waters affected by these projects is 5.0 mg/L dissolved oxygen per liter. This was the concentration established for Alternative 2.

The most recent USEPA publication on DO criteria (Ref. 4-4) lists a 7-day mean concentration of 6.0 mg/L and an instantaneous minimum concentration of 5.0 mg/L as the desirable criteria to protect warm water aquatic resources.

A Science Advisory Board review of these criteria (Ref. 4-7) suggests that they may be too low, because they are based on studies that have

shown sublethal deleterious effects on fish at those concentrations. That report recommends criteria that are 0.5 mg/L higher, or 6.5 and 5.5 mg/L for 7-day mean and instantaneous dissolved oxygen concentrations respectively. FERC alternatives 3 and 4 adopt the 6.5 mg/L concentration as a "no-effects" level. These alternatives require "aeration spillage at hydroelectric projects in sufficient amounts to maintain the 'no-effects' DO concentration and to allow no reduction in aeration when DO concentrations are below this threshold." (Ref. 4-8)

Antidegradation Policies and Maintenance of "Pre-project" or "Existing" Conditions. In the initial letters of comment on the Draft EIS, only West Virginia indicated they had antidegradation regulations that apply to the waters considered in the EIS. USEPA also has a formal antidegradation policy (40 CFR Par 131.12). This policy states:

> "Where the quality of waters exceed levels necessary to support propagation of fish, shellfish, and wildlife and recreation in and on the water, that quality shall be maintained and protected unless the State finds, after full satisfaction of the intergovernmental coordination and public participation provisions of the State's continuing planning process, that allowing lower water quality is necessary to accommodate important economic or social development in the area in which the waters are located."

The West Virginia water quality regulations (as quoted by FERC, Appendix J, page J-18) uses the same USEPA wording with the following addition:

> "If limited degradation is allowed, it shall not result in injury or interference with existing stream water uses or in violation of State or Federal water quality criteria that describe the base levels necessary to sustain the national water quality goal uses of protection and propagation of fish, shellfish and wildlife and recreating in and on the water."

A December 12, 1988, letter from USEPA references 40 CFR 131.12 (above) as justification for maintenance of pre-project conditions. The letter, however, deletes the last half of that policy beginning with the word "unless". In the Final EIS, FERC maintains that "the environmental and economic benefits of hydropower development (as

recommended by staff) that would not cause violations of the State criteria would justify the limited degradation allowed in this regulation", and as predicted by the water quality modeling efforts. In turn, the agencies argue that FERC does not provide adequate justification of "benefits" to justify any reduction in existing water quality. They also question the results of the modeling effort because they believe the data base was inadequate to properly calibrate the model.

Regarding the modeling of a fifth alternative ("pre-project DO conditions") requested by the USFWS, USEPA, and the states, FERC offered the following points.

1) Requirements for strict maintenance of "pre-project" or "existing" DO concentrations would prohibit power generation at many of the dams, without resulting in significant water quality benefits during times when DO concentrations are not low enough to affect aquatic organisms.

2) The FERC staff also recommend that "DO concentrations upstream and downstream of each project be monitored and the data provided electronically to ORSANCO[3], and that water quality management agencies and FERC be authorized to require increased spill flows during low DO events. In addition, formation of a basin-wide group to monitor and manage DO at the projects is also recommended. Staff feels these recommendations (1) will fully protect the aquatic environment, (2) are practical to implement, and (3) will allow generation of significant amounts of power."[4]

3) There are significant technical problems in determining what "pre-project conditions" are. DO conditions at any point vary continuously over a wide range with concentrations being controlled by temperature, waste loadings, river flows, and biological processes. There is no single set of pre-project DO conditions for the system.

4) One or two years of DO measurements are not adequate to define baseline conditions. Rather, the FERC staff believed it to be more prudent, as well as more practical, to maintain a specific DO standard, based on the best available scientific criteria and selected to avoid impacts to fish.

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[3] Ohio River Valley Water Sanitation Commission.

[4] Ref. 4-8, page J-19, citations deleted.

The "anti-degradation" argument, therefore becomes a disagreement over the meaning of the term. One interpretation, as put forth by the resource agencies, is that there should be no reduction in a given specific water quality parameter. The alternative interpretation, as put forth by FERC, would permit a lowering of a specific parameter for accomplishment of other, off-setting, benefits. This would be allowed only if such lowering does not "result in injury or interference with existing stream water uses or in violation of State or Federal water quality criteria that describe the base levels necessary to sustain the national water quality goal uses of protection and propagation of fish, shellfish and wildlife and recreating in and on the water."

Data Adequacy

The question of data adequacy, as exemplified in the referenced FEIS, has many aspects. Among these are:

1) Adequate for what purpose?
2) What criteria determine adequacy?
3) How do you obtain "adequate" data?

As evidenced by the agency comments on the Draft EIS, and the FERC staff reply thereto, there is a need for agreement on the approach as well as objective in evaluating project impacts on dissolved oxygen concentrations. As discussed in the previous section, the resource agencies did not agree with the objectives (the alternative DO scenarios) proposed by the FERC staff. Neither did they agree with the approach adopted by the staff.

Modeling of DO concentrations as affected by 30 dams, distributed over 500 river miles of five rivers is a major undertaking. The agencies requested that DO concentrations be monitored for one or two years at each proposed site to define "existing conditions", and to fill in data gaps prior to licensing.

The response by the FERC staff indicated:[5]

1) The agencies did not appear to consider the "significant technical problems that arise in determining what 'pre-project conditions' are."

2) "One or two years of DO measurements are not adequate to define baseline conditions. For example, DO measurements made in the summers of 1987 and 1988, as recommended by several agencies, represent unusually low DO conditions and if used as a baseline could result in significant degradation. In addition, the experience of project applicants that attempted to monitor DO at their sites indicated that frequent gaps in monitoring data must be expected and that the monitors tend to underestimate DO concentrations. Staff believes that having applicants monitor DO for one or two years would not provide information adequate to base spill flow requirements on, and would be an unjustified burden on license applicants."

3) "The staff does not believe that collection of one or two years of DO measurements at each dam would describe the so-called existing DO conditions, due to the high variability in DO concentrations and the problems and error that can be expected in monitoring DO. Instead, the staff chose to measure the existing aeration rates at each dam, which were used in models to quantify the effects of hydropower."

4) "DOI and other agencies have not defined what is meant by 'pre-project' or 'existing conditions', or how these conditions would be determined from measured DO data for application to anti-degradation criteria. Staff does not believe it is justifiable to require collection of data that (1) will contain gaps and error due to monitoring problems, (2) will not define the historic range of conditions adequately, and (3) will be used to determine DO criteria when the method used for such a determination has not been specified and may not take into account effects on either aquatic organisms or generating capacity.

"Staff believes that it is more prudent as well as more practical to maintain a specific DO criteria, based on the best available scientific research and selected to avoid impacts to fish, than to try to maintain undefined and poorly measured 'existing conditions'. This approach is especially appropriate in rivers whose water quality is as highly affected by development as are the Allegheny, Monongahela, Muskingum, and Ohio rivers. Staff be-

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[5] FEIS, pages J-17 to J-19.

> lieves that much more success will be had in implementing a relatively simple DO management objective (maintaining concentrations of at least 6.5 mg/L) than in attempting to implement DOI's proposed anti-degradation policy on rivers whose water quality is already heavily affected by man. The cumulative nature of hydropower impacts on DO would make implementation of anti-degradation DO criteria that vary between sites and seasons extremely complex and difficult to enforce."

At present, the question of what constitutes data adequacy remains unresolved. A January 13, 1989 letter from the USFWS, the Ohio Department of Natural Resources, and the Pennsylvania Fish Commission states that "insufficient data have been made available to the state and federal fish and wildlife agencies to allow their independent analysis and evaluation of" the FERC Alternative 4 and an "anti-degradation" (i.e. maintenance of pre-project conditions) alternative. The letter continues, "the information and data used to develop the DO model in the EIS are insufficient to evaluate the magnitude and duration of water quality impact expected in the Allegheny, Monongahela and Ohio Rivers... These data are not required if the states' anti-degradation objectives are maintained." Again, the issue reverts to the definition of "anti-degradation".

Cumulative Impacts

Another area of difference between the FERC staff and the agencies is what constitutes adequate evaluation of cumulative impacts. The agencies maintain that all licensed, exempted, proposed, and reasonably potential hydroelectric projects in the entire Ohio River Basin be included in the analysis.

FERC views the function of the cumulative impact analysis to be the evaluation of all reasonably foreseeable cumulative or interactive impacts, not to optimize basin development or evaluate numerous "what if" scenarios.

Thirty dams were considered in the FERC analysis. This includes all projects (existing and those with license applications accepted) whose operation can reasonably be expected to have cumulative and interactive effects on water quality. Preliminary hydropower permits are not viewed collectively as reasonably foreseeable actions. Nor

do preliminary permit applications contain sufficient information to allow study in the environmental impacts of the development.

In the future, if new license applications are accepted for projects within the study reach, the impacts of such projects, including impacts on dissolved oxygen concentrations, will be assessed in relation to any other projects, proposed or existing, with which there would be cumulative or interactive impacts.

Equal Consideration

As discussed in Section 4.1, the Electric Consumers Protection Act of 1986 (ECPA) required that FERC give equal consideration to environmental concerns in the licensing process. Section 10(j)(2) of the Federal Power Act, as added by ECPA, specifies that, if "the Commission does not adopt in whole or in part a recommendation of any such [resource] agency, the Commission shall publish" a discussion of the relative positions of the agencies and why the resource agency requests were not accepted.

The letter from the USFWS commenting on the draft EIS implies that FERC is violating the spirit, if not the letter, of the law by recommending an alternative that does not prohibit degradation of existing dissolved oxygen concentrations.

The hydropower development alternative (No. 4), as recommended by the FERC staff, provides adequate environmental protection associated with multiple hydro development in the Upper Ohio River Basin. The FERC staff believes that this alternative, as described in the FEIS and in the responses to the agency comments on the draft EIS, is in full compliance with ECPA.

Section 5

FISHERY CONSIDERATIONS

5.1 BIOLOGICAL EFFECTS OF LOW DISSOLVED OXYGEN LEVELS

Of the many degrading alterations to water quality that affect fisheries, reduction of DO concentrations is generally the most common and important. When it is above concentrations essential for maintaining aquatic life, yet not in excess of need, dissolved oxygen (DO) acts as a limiting factor, much as food availability does, setting intermediate sublethal limits to growth of fish. The effects of reduced DO on aquatic life, particularly that of lethality, have been investigated as thoroughly as those of any water quality alteration resulting from pollution or reservoir operation. Generalities drawn from numerous studies are highlighted in the following section on biological responses, with more detailed information presented in individual species accounts.

Sensitivities of the salmonids (trout, chars, salmon, and whitefishes) to low DO have been investigated more thoroughly than for any other aquatic organisms. Their great economic value, ready availability of various life stages from hatchery stocks, and relative ease of maintenance under laboratory conditions have strongly biased DO research towards this family of coldwater fishes. Most of the available information for fishes on lethality, growth, feeding, physiology, early development of life stages and swimming speed performance, has also been gained under laboratory-controlled conditions. Two major limitations of this information are that, by design, laboratory studies typically attempt to preclude synergistic environmental or species interactions and secondly, the tremendous variability of methodologies used. Though these studies represent the best available information, most reports do not meet the rigorous, standardized procedures now typically used by USEPA for establishment of chronic toxicity or sublethal effects, by not including

either a full life cycle or the sensitive larval stage, or the length of tests is of too short-term for adequate appraisal of long-term survival and growth.

Physiological Basis

The physiological responses of salmonids to varying degrees of hypoxia (low dissolved oxygen concentration) have been investigated in a great number of studies (Ref. 5-1) measuring metabolic and cardiovascular responses to rapid, short-term exposures of fish to low DO concentrations. The main utility of these studies for standards development and application has been indirect (Ref. 5-2), i.e. allowing understanding of how low DO levels physiologically act to affect fish production. The incipient response thresholds for selected North American fish species (Ref. 5-3) presented in Table 5-1 provide an indication of initial biological responses to low dissolved oxygen concentrations. Though intermediate assumptions are manifold, good correlations have been observed between physiological relationships such as blood dissociation curves for rainbow trout (Ref. 5-4) and reduction in growth of trout (Ref. 5-5 and Ref. 5-6), the more important readily-measured, "end product" of physiological processes used in evaluating relative impairment of production.

For non-salmonids the bulk of physiological research has been on relating resting oxygen consumption rates and low DO levels in order to define "critical" oxygen concentrations. This is the point where a reduction in resting metabolic rate is observable, resulting in greatly reduced energy available for growth and activity, a decrease in oxygen to the tissues and a partial shift to anaerobic energy processes. In general, critical oxygen concentrations for a variety of non-salmonid fishes fall between 2 and 4 mg/L with higher temperatures yielding higher critical oxygen concentrations.

Direct Acute Lethality. Regarding lethal concentrations of low DO, North American salmonid data summarized by Douderoff and Shumway (Ref. 5-1) indicated mortality or loss of equilibrium usually occurred between 1 and 3 mg/L in tests of variable length for species of the genera Coregonus, Oncorhynchus, Salmo, Salvelinus and Stenodus (Table 5-2). For exposure times less than 3.5 days, DO concentrations of 3 mg/L or higher should produce no direct mortality of

Table 5-1

INCIPIENT OXYGEN RESPONSE THRESHOLDS FOR VARIOUS NON-SALMONID FISH

Species	Size	Temp. (°C)	mg O_2/liter	Response To Oxygen Level
Brown, bullhead *Ictalurus nebulosus*	43-127 gm	9-10	6.95-6.80	Onset dependent on oxygen uptake
carp *Cyprinus carpio*	77-350 gm	10	3.59	Standard oxygen uptake
	30-600 gm	20	4.71	elevated (depressed at lower levels)
" "	235-785 gm	13.3-25	5.39-4.34	Blood ceased to be fully saturated with O_2 below this level
Walleye *Stizostedion vitreum*	2-yr old	22	4-2.0	Loss of negative phototaxis
			5.5-4.0	Increased mobility, "darting behavior"
Largemouth bass *Micropterus salmonides*	5-9 cm	--	4.5	Some indication of avoidance behavior
			1.5	Marked avoidance
Largemouth bass *Micropterus salmonides*	juvenile	25	5-6	Maximum swimming speed reduced below this level
Bluegill *Lepomis macrochirus*	5-9 cm	--	3.0	Some avoidance behavior
			1.5	Strong avoidance
American shad *Alosa sapidissima*	--	--	3.0	Threshold for migration through polluted areas
Northern pike *Esox lucius*	from fertilization to feeding larvae	15, 19	3.35-3.09	Necessary oxygen level for proper hatching, survival, and development

NOTE: Response levels reported are incipient oxygen levels where effects first become apparent, thus providing a "biological indication" of the onset of hypoxis stress.

(Ref. 5-1)

Table 5-2

SUMMARY OF LETHAL LEVELS OF DISSOLVED OXYGEN PUBLISHED AFTER THE YEAR 1937

Species of fish Scientific and Common Names	Age or Size	Dissolved O_2 mg/l[a/]	Deaths	Exposure[b/]	Temp C	Reference	Remarks[c/]
SALMONIDAE							
Coregonus autumnalis Whitefish, Baikal omul	larvae	1.3-1.5	First	Declining O_2	-	Meshcheriakova and Cherniaev (1963)	
Coregonus nasus	1 day	1.9*	-	Declining O_2	12	Chernikova (1964)	*Cessation of opercular movement
Broad whitefish	120 days	1.9*	-	Declining O_2	12	Chernikova (1964)	*Same as above
	209 days	1.1*	-	Declining O_2	10	Chernikova (1964)	*Same as above
Oncorhynchus gorbuscha Pink salmon	Fingerling	2.1*	-	-	17	Privolnev (1963)	*Reported threshhold concentration; methods unknown
Oncorhynchus keta Chum salmon	Fingerling	2.0*	-	-	17	Privolnev (1963)	*Same as above
Oncorhynchus kisutch Coho salmon	4-11 cm	1.1-1.7	0-83%	Constant O_2 24 hours	12-20	Davison et al (1959)	
	4-11 cm	1.5	15%	Constant O_2 24 hours	22	Davison et al (1959)	
	4-11 cm	2.1	3%	Constant O_2 24 hours	24	Davison et al (1959)	
	Juvenile	1.7-2.0*	0-90%	Constant O_2 24 hours	20-22	McNeil (1956)	*CO_2 concentrations 3 to 20 mg/l
	3-4 g	1.1-1.3	71%	Constant O_2 18-25 hours	12-13	Townsend et al (1938)	*Loss of equilibrium
	Yearling	1.2-1.6	50%	Constant O_2 24 hours	14	Townsend and Earnest (1940)	*Loss of equilibrium

Table 5-2 (continued)

Species of fish Scientific and Common Names	Age or Size	Dissolved O_2 mg/l[a]	Deaths	Exposure[b]	Temp C	Reference	Remarks[c]
Oncorhynchus mykiss Rainbow trout	6 mo	1.3-1.6*	50%	Constant O_2 24 hours	13-20	Alabaster et al (1957)	*Range of estimated values; no CO_2
	6 mo	2.6-2.7%	50%	Constant O_2 24 hours	13-20	Alabaster et al (1957)	*Range of estimated values; CO_2 concentration 30 mg/l
	Yearling	1.3-2.5	First*	Declining O_2	11-22	Burdick et al (1954)	*Loss of equilibrium
	Yearling	1.1-1.8	50%*	Declining O_2	11-22	Burdick et al (1954)	*Loss of equilibrium
	Yearling	0.8-1.4	100%*	Declining O_2	11-22	Burdick et al (1954)	*Loss of equilibrium
	4.4 g	2.5	50%	Declining O_2	22-24	King (1943)	
	10 cm	2.9	None	Constant O_2 3.5 days	10-20	Downing and Merkens (1957)	
	10 cm	2.4-3.1	50%	Constant O_2 7 days	16-20	Downing and Merkens (1957)	
	Juvenile	1.6-1.7*	50-70%	Constant O_2 24 hours	16-20	McNeil (1956)	*CO_2 concentrations 3-8 mg/l
	Yearling	1.5-1.6	10%	Constant O_2 18-24 hours	11-13	Townsend et al (1938)	*Loss of equilibrium
	Yearling	1.4/less	100%*	Constant O_2 18-24 hours	11-13	Townsend et al (1938)	*Loss of equilibrium
	-	0.8-1.2	First	-	17	Privolnev (1954)	Methods unknown
	2 yr	0.5-1.5*	-	Declining O_2	15	Streltsova (1964)	*Fish acclimated to 3 and 19 mg/l O_2
	88-235 mg	1.1-1.6*	-	Declining O_2	15	Streltsova (1964)	*Same as above
Oncorhynchus nerka Sockeye salmon	Adult	2.3-2.7	Most*	Declining O_2	21-23	Chapman (1940)	*Dead or lost equilibrium
Oncorhynchus tshawytscha Chinook salmon	Adult	2.3-2.7	Most	Declining O_2	21	Chapman (1940)	*Dead or lost equilibrium
	Fingerling	1.7-1.8	50%	Constant O_2 24 hours	20	Katz et al (1959)	
Salmo clarki Cutthroat trout	11-17 cm	1.2-1.4	50%*	Constant O_2 18-24 hours	11	Townsend et al (1938)	*Loss of equilibrium

Table 5-2 (continued)

Species of fish Scientific and Common Names	Age or Size	Dissolved O_2 mg/l[a/]	Deaths	Exposure[b/]	Temp C	Reference	Remarks[c/]
Salmo salar Atlantic salmon	Newly-hatched	0.3*	None	Constant O_2 5 days	7	Bishai (1960)	*Lowest tested O_2 level tolerated by all
	40 days	0.7*	None	Constant O_2 2 days	5	Bishai (1960)	*Same as above
	80 days	2.8*	None	Constant O_2 3 days	9	Bishai (1960)	*Same as above
	135 days	2.2*	None	Constant O_2 2 days	16	Bishai (1960)	*Same as above
	3-6 g	0.7-1.6*	-	-	-	Nikiforov (1953)	*Range of lethal levels for individual fish; methods unknown
	7 cm	2.2*	None	Constant O_2 5 days	8	Lindroth (1949)	*Not reported as a tolerance limit
	Fingerling	1.5*	-	-	15	Privolnev (1963)	*Reported threshhold concentration; methods unknown
	Yearling	1.9*	-	-	16	Privolnev (1963)	*Same as above
	36 days	3.1-3.7	-	Declining O_2	15	Privolnev (1947)	
	107 days	1.2-1.3	-	Declining O_2	15	Privolnev (1947)	
Salmo trutta Brown trout	Yearling	1.6-2.8	First*	Declining O_2	9-21	Burdick et al, (1954)	*Loss of equilibrium
	Yearling	1.5-2.5	50%*	Declining O_2	9-21	Burdick et al, (1954)	*Loss of equilibrium
	Yearling	1.3-2.3	100%*	Declining O_2	9-21	Burdick et al, (1954)	*Loss of equilibrium
	-	1.1-3.3*	First	-	0	Privolnev (1954)	*Methods unknown
	Newly-hatched	0.3-0.6*	None	Constant O_2 5 days	7	Bishai (1960)	*Lowest O_2 level tolerated by all
	40 days	1.2*	None	Constant O_2 2 days	5	Bishai (1960)	*Same as above
	2.9 g	3.2	50%	Declining O_2	22-24	King (1943)	
	80 days	1.6*	None	Constant O_2 3 days	9	Bishai (1960)	*Same as above
	180 days	1.8*	None	Constant O_2 2 days	16	Bishai (1960)	*Same as above

Table 5-2 (continued)

Species of fish Scientific and Common Names	Age or Size	Dissolved O_2 mg/l[a/]	Deaths	Exposure[b/]	Temp C	Reference	Remarks[c/]
Salvelinus fontinalis Brook trout	17 g	<2.0*	100%	Declining O_2	17-20	Black et al (1954)	*CO_2 tensions 0-40 mm Hg
	Yearling	2.0-3.4	First*	Declining O_2	12-21	Burdick et al, (1954)	*Loss of equilibrium
	Yearling	1.6-2.6	50%*	Declining O_2	12-21	Burdick et al, (1954)	*Loss of equilibrium
	Yearling	1.2-1.7	Last*	Declining O_2	12-21	Burdick et al, (1954)	*Loss of equilibrium
	27 g	Above 2.5	None	Constant O_2 24 hours	12-23	Graham (1949)	
	27 g	Below 1.9	100%	Constant O_2 24 hours	12-23	Graham (1949)	
	Fingerling	1.0-1.8%	50%	Constant O_2 3.5 days	9	Shepard (1955)	*Est. incipient lethal levels for varying acclimation O_2 levels
	4.5 g	2.3	50%	Declining O_2	21-23	King (1943)	
Stenodus leucichthys Inconnu	-	4.0-4.5	First	-	0	Privolnev (1954)	Methods unknown
	4.7 g	.25-2.6*	-	-	2	Karzinkin (1942)	*Reported lethal threshhold; methods unknown

(Ref. 5-2)

a The symbol < preceding an O_2 concentration value in this column indicates that several or numerous lethal O_2 concentrations reported were all less than (often much less than) the value shown.

b "Declining O_2" signifies gradual reduction of O_2; unless otherwise noted under Remarks, O_2 was reduced by respiration of text fish.

c See Ref. 5-1.

d The asterisk (*) is used to indicate to which item or items in the columns at the left the remark pertains or is most pertinent.

salmonids (Ref. 5-2). The differences between DO levels causing complete mortality and those allowing complete survival of brook trout was only about 0.5 mg/L for exposures of less than one week (Ref. 5-7 and Ref. 5-2), indicating a well-defined threshold for lethal effects. Recent chronic tests using early life history stages of salmonids (Ref. 5-8, 5-9, and 5-10) generally confirm these lethal levels.

With the exception of some larval life stages, non-salmonids seem to be less sensitive to low DO levels than salmonids. Data is limited to only a very few non-salmonid species (Figure 5-1). In most cases, exposure to 3 mg/L DO in acute laboratory tests (24 to 96-hours in length) result in no mortality. Several species of non-salmonids seem to be able to survive acute exposures to DO levels below 1 mg/L for several days (Ref. 5-11 and Ref. 5-12), but short-term tests reveal nothing about the latent effects on longer-term survival. Additionally, there is no data regarding the effects of repeated short-term exposures.

An unusual source of mortality involving dissolved oxygen is that of supersaturation, or the over abundance of total dissolved gases (Ref. 5-13). By the 1970s, it was recognized that gas bubble trauma occurring in salmonids resulted from supersaturation of all atmospheric gases including oxygen, not just nitrogen. These problems, which typically have occurred at hydroelectric dams which release deeply plunging flows, were thoroughly reviewed by Harvey (Ref. 5-14), Fickeisen and Schnieder (Ref. 5-15) and Weitkamp and Katz (Ref. 5-16). Several dams with problems of this sort are located on salmonid streams and rivers of the Pacific Northwest.

Growth. For six salmonid species in the genera Oncorhynchus, Salmo and Salvelinus, USEPA (Ref. 5-2) and JRB Associates (Ref. 5-163) summarized data from 24 tests of DO effects on growth (Table 5-3). Median growth rate reductions from these tests were 7, 14 and 25 percent for fish held at 6, 5, and 4 mg/L, respectively. Reductions in growth at DO levels above 6 mg/L were rarely statistically significant; those between 4 and 6 mg/L were typically slight or moderate, even at exposures of longer duration; but those below 4 mg/L were severe.

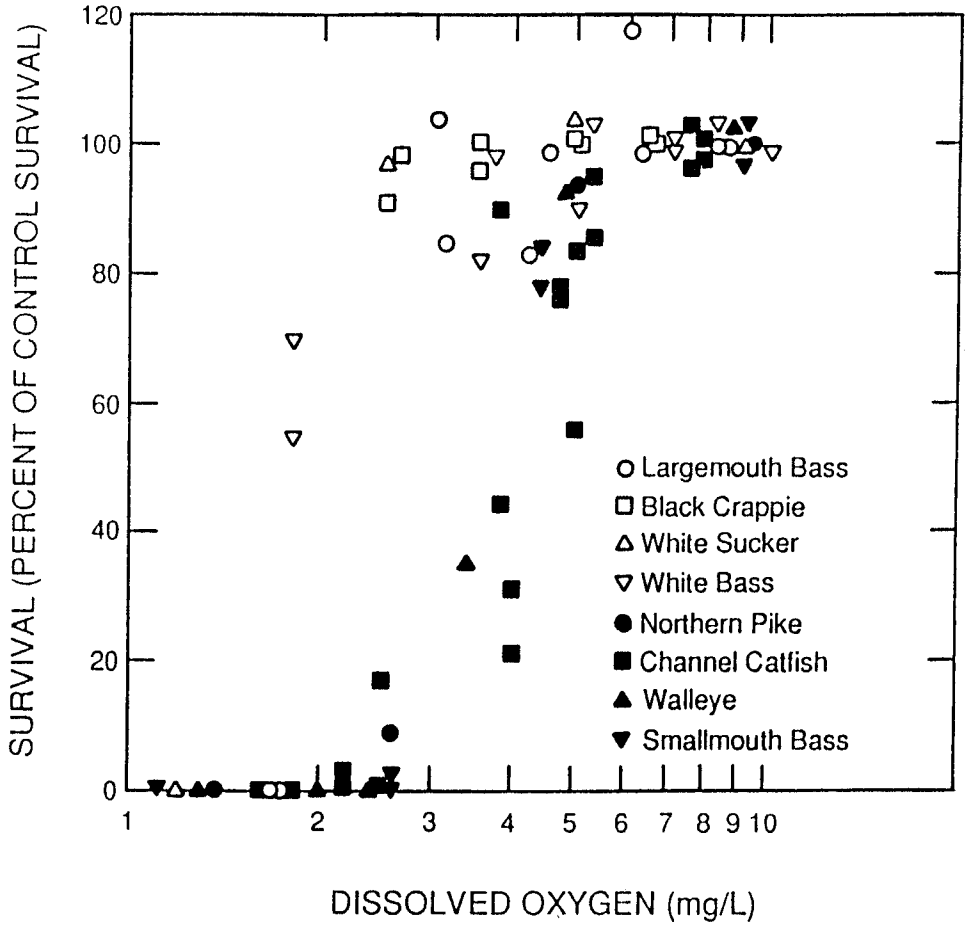


Figure 5-1. Effects of continuous exposure to various mean DO concentrations on survival of embryonic and larval stages of eight nonsalmonid fish species. Minima recorded in these tests averaged about 0.3 mg/L below the mean concentrations.

Table 5-3

PERCENT REDUCTION IN GROWTH RATE OF SALMONIDS AT VARIOUS DO CONCENTRATIONS EXPRESSED AS THE MEDIAN VALUE FROM (N) TESTS WITH EACH SPECIES

Dissolved Oxygen mg/L	Species (Number of Tests)					
	Chinook Salmon	Coho Salmon (12)	Sockeye Salmon (1)	Rainbow Trout (2)	Brown Trout (1)	Lake Trout (2)
9	0	0	0	0	0	0
8	0	0	0	1	0	0
7	1	1	2	5	1	2
6	7	4	6	9	6	7
5	16	11	12	17	13	16
4	29	21	22	25	23	29
3	47	37	33	37	36	47
Median Temp. (°C):	15	18	15	12	12	12

(Ref. 5-3)

Growth of salmonids is most sensitive to effects of low DO at higher temperatures when their metabolic requirements are highest. Increasing temperatures and decreasing DO concentrations are conditions commonly occurring both within reservoirs and their regulated rivers as summer stratification of reservoirs strengthens. Warren et al. (Ref. 5-6) conducted tests on the influence of dissolved oxygen and temperature on growth rates of coho and chinook salmon (Table 5-4 and Table 5-5). Major findings of this excellent study were that: the largest reductions of growth rate were at high temperatures (e.g., 17.8°C to 21.7°C for chinook); the thresholds where effects occurred, rose to higher DO levels with increased temperature; and that extrapolation of probable DO reduction effects from tests conducted at lower temperatures would drastically underestimate effects of low DO at higher temperatures. Extrapolation of data summarized in Table 5-3 to higher temperatures would thus probably significantly underestimate effects of low DO on these other salmonid species. However, in the absence of more site-specific data (Ref. 5-2) and information on such factors as current velocity, activity level and food availability presented in some of the following individual species accounts, these data sets represent the best estimators of the effects of low DO on growth of salmonids.

Reproduction. DO concentration does appear to have an effect on reproductive status and the success of fishes, but no information is presently available concerning the effects of low DO on fecundity, fertility or reproduction of salmonids and very little for non-salmonids. A complete life cycle exposure to low DO concentrations has been performed only for the fathead minnow (Ref. 5-17). No spawning occurred at 1 mg/L, fecundity was reduced at 2 mg/L, larval growth was less at DO concentrations below controls, and larval survival was related to DO concentration (6% survival at 3 mg/L; 25% at 4 mg/L; 66% at 5 mg/L and 50% in controls). In large channel tests (see Appendix D), the occurrence of mature spawning bluegill appeared severely impacted at DO concentrations below 6.4 mg/L. This finding is in apparent contradiction of Siefert and Herman (Ref. 5-18), who reported normal centrarchid spawning at DO concentrations as low as 2 mg/L.

Table 5-4

INFLUENCE OF TEMPERATURE ON GROWTH RATE OF CHINOOK SALMON
HELD AT VARIOUS DISSOLVED OXYGEN CONCENTRATIONS

Dissolved Oxygen mg/L	Percent Reduction in Growth Rate at 8.4 °C	13.0 °C	13.2 °C	17.8 °C	18.6 °C	21.7 °C
9	0	0	0	0	0	0
8	0	0	0	0	0	0
7	0	0	4	0	1	2
6	0	0	4	0	6	2
5	0	0	16	16	13	34
4	7	4	25	33	23	65
3	26	22	36	57	36	100

(Ref. 5-4)

Table 5-5

INFLUENCE OF TEMPERATURE ON GROWTH RATE OF COHO SALMON HELD AT VARIOUS DISSOLVED OXYGEN CONCENTRATIONS

Dissolved Oxygen mg/L	Percent Reduction in Growth Rate at 8.6 °C	12.9 °C	13.0 °C	18.0 °C	21.6 °C	21.8 °C
10	0	0	0	0	0	0
9	0	0	0	5	0	0
8	0	1	2	10	0	0
7	1	4	6	17	0	6
6	4	10	13	27	0	1
5	9	18	23	38	0	7
4	17	29	36	51	4	19
3	28	42	51	67	6	37

(Ref. 5-5)

Behavior and Swimming Performance. Fish can detect low DO conditions and will attempt to actively avoid such areas. Salmonids (chinook and coho salmon) avoid concentrations of 3.0 mg/L or lower (Ref. 5-19). Centrarchids (largemouth bass and bluegill) show definite avoidance of DO concentrations of 1.5 mg/L (Ref. 5-19). As an example of where "more" is not necessarily better, the behavior of normally quiescent yolk-sac larvae of largemouth bass was elevated to unusually high activity at 4 to 5 mg/L (Ref. 5-20), which could result in much greater predation to larvae. Age appears to be a factor in the ability to detect differences in DO level. Young brown trout and Atlantic salmon 6-26 weeks of age avoided concentrations of 3 to 4 mg/L (Ref. 5-21), but younger fish apparently could not detect the differences. Swimming performance of largemouth bass (Ref. 5-22 and Ref. 5-23), as for salmonids, is reduced and most sensitive to low DO when temperatures are lower.

Within reservoirs experiencing hypolimnetic DO depletion, the distribution of striped bass, largemouth bass, and walleye suggests they are sometimes detecting and actively avoiding areas of low DO. Chittenden (Ref. 5-24 and 5-25) found striped bass distribution to be bounded by the 3 mg/L isopleth and Coutant (Ref. 5-26) found them to avoid reservoir concentrations of low DO in the 0.5 to 2.5 mg/L range. In one study, largemouth bass concentrations were found to be most strongly influenced by the DO level, with the greatest number of fish preferring areas where DO levels were more than 2 mg/L (Ref. 5-27). Scherer (Ref. 5-28) documented the greater occurrence of adult walleye in reservoir areas with DO concentrations greater than 3 to 5 mg/L. Dendy (Ref. 5-29) documented the movement of walleye out of areas experiencing DO levels of 0.0 to 1.5 mg/L into upper reservoir strata. The normal phototactic behavior (light avoiding) of walleye is no longer prevalent if DO concentrations fall to 2 to 4 mg/L. Under these conditions, the fish move into shallow, more oxygenated waters (Ref. 5-28). As hypolimnetic oxygen-depletion spreads and summer epilimnetic temperatures rise above thermal tolerances for that species, fish moving to shallower waters to avoid DO-depleted areas may experience a thermal-oxygen "squeeze," resulting in metabolic stress, disruption of feeding or increased mortality rates.

Creel characteristics of a fishery will also be affected by changes in fish behavior. Weithman and Haas (Ref. 5-30) reported decreasing harvest rates for the rainbow trout fishery with decreasing DO concentrations in Lake Taneycomo of Missouri. Consistent with the findings of Warren et al. (Ref. 5-6) relating growth impairment to reduced food intake under low DO conditions, they postulated that feeding behavior was impaired.

Early Life Stages. The early life stages of many salmonid species occur when the eggs or larval fish are buried in gravel substrates. Dissolved oxygen levels in intergravel areas are dependent on DO diffusion, rates of water percolation or convection, and the respiration of all gravel-dwelling organisms (Ref. 5-2). The inter-relationship of flow and DO level available to developing embryonic and larval salmonids is important. Dissolved oxygen requirements of early life stages of salmonids do not differ significantly from those of adults, but they may be subjected to much lower DO levels intergravelly than that measured in overpassing waters. Intergravel DO concentrations may be depleted even when DO concentrations in overpassing waters may be at acceptable levels. With adequate flow, Brannon (Ref. 5-31) and Chapman and Shumway (Ref. 5-32) reported decreases of less than 10 percent by continuous exposure of trout and salmon to DO concentrations as low as 3 mg/L. However, available studies based on field observations (Ref. 5-33 and Ref. 5-34) indicate that developing salmonids buried in natural redds (i.e., nests) are exposed to DO levels approximately 3 mg/L lower than that of overpassing waters. This 3 mg/L differential was assumed in development of national DO standards for salmonid species.

Exposure of salmonid embryos and larvae to low concentrations of DO result in delays in embryonic development and hatching which could have significant effects on survival or growth of alevins or larvae (Ref. 5-35 and Ref. 5-8), even at concentrations as high as 6 mg/L for some species (Ref. 5-36 and Ref. 5-8); and increased mortality of embryos (Ref. 5-37). Effects of low DO are greatest during late embryonic development when critical DO levels are highest (Ref. 5-38).

For non-salmonids, larval and juvenile stages are most often more sensitive to low DO than other life stages. Several investigations have indicated reduced survival or significant damage to young of non-salmonids in the range of three to six mg/L DO (Ref. 5-2). Lethality data (Figure 5-1) on non-salmonids show that some species are more tolerant (largemouth bass, black crappie, white bass, and white sucker) than others (channel catfish, walleye, northern pike, smallmouth bass). The latter three fishes are often considered coolwater species, or are grouped with salmonids as sensitive cold-water species. More detailed discussions for young non-salmonid fishes are included in the individual species accounts.

Fishery Diversity

Though only semi-quantitative and not defining the actual long-term exposure levels experienced by fish communities, three pertinent field studies relating DO concentrations and diversity of fish assemblages have been conducted. Reporting numerous DO concentrations and fish collections from 982 stations in streams and rivers from June to September 1930-1935, Ellis (Ref. 5-39) concluded that 5 mg/L was the lowest concentration at which a good mixed assemblage of warmwater fish species could be maintained in inland freshwater. A two year survey of the Ohio River (Ref. 5-40) indicated that fish were more abundant at DO concentrations of 3 to 5 mg/L than at lower concentrations, but still showed a greater incidence of parasitization, sickness and deformity than fishes in areas with greater than 5 mg/L DO. Working in the Wisconsin River, Coble (Ref. 5-41) reported that sport fish made up a significantly greater proportion of fish populations in areas with mean summer DO concentrations greater than 5 mg/L. In spite of the number of questions these studies raise, all three indicate that composition, abundance and condition of these non-salmonid fish assemblages did not noticeably improve with increases in DO above 5 mg/L.

Fluctuating Concentrations Of Dissolved Oxygen

Fish and most other aquatic organisms in rivers and reservoirs are exposed to natural fluctuations in seasonal and diurnal DO concentrations. Research has shown that these conditions are quite different from exposure to constant DO concentrations, such as those typically maintained in laboratory studies. Additionally, biota of tailwaters

and rivers regulated by hydroelectric dams can be exposed to even more drastic DO fluctuations on a daily basis. For daily or longer-term exposures to cyclic DO levels, minimum concentrations appear more important than mean values in determining the magnitude of the effects on fish. Studies by Fisher (Ref. 5-42) and Whitworth (Ref. 5-43) concerning the effects of daily DO cycling indicate that growth of fish was much less than would have been estimated from daily mean DO concentrations. Growth of fish was only slightly better than that attainable by constant exposure to daily minimum DO values.

Atypically, most information presently available on the effects of fluctuating DO concentrations has come from non-salmonid, non-cold-water species. As in the case of constant DO concentrations, the growth responses of groups of warmwater and coolwater fishes to fluctuating DO levels differed among species. With any fluctuation from a minimum of 2 mg/L to maxima between 4 and 17 mg/L, largemouth bass showed reduced growth from that which would be expected by exposure to a constant mean concentration (Ref. 5-44). Channel catfish growth was significantly impaired at fluctuations from about 3.1 mg/L down to 1.0 mg/L, but not at higher concentrations (Ref. 5-45). As found in constant DO studies, lesser sensitivity to DO fluctuations was observed for the yellow perch (Ref. 5-45), i.e., growth impairment was not observed for fluctuations from about 3.8 to 1.4 mg/L, even though food intake was reduced. Spawning of mature black crappie was unsuccessful at DO fluctuations between 1.8 and 4.1 mg/L, but successful at fluctuating higher mean DO levels where the degree of fluctuation around the mean DO concentration was similar (Ref. 5-46).

The reader is referred to Appendix D, where previously unpublished TVA data demonstrate that daily DO fluctuations changing from an average daily minimum of 3.5 mg/L to a mean daily average of 4.7 mg/L (daily maximum averaged 6.0 mg/L), significantly impaired the growth of rainbow trout in large experimental channels. Similar fluctuations around higher mean daily averages (6.3, 7.9 and 12.3 mg/L) had no significant impact on growth. TVA experiments using rainbow trout held in aquaria with DO concentrations either maintained at constant levels or varied in different manners (simulating releases from hydroelectric facilities), demonstrated that the growth of rainbow

trout was impaired at all levels below saturation, but that discharge regimes could probably be modified to reduce growth impairment to fish. More importantly, and in contrast to the overall findings of Fisher (Ref. 5-42) and Whitworth (Ref. 5-47), growth rates for daily periods of 7 to 9-hours of DO reduced to 4 mg/L (five days per week) and 2 to 4-hours of reduction to 3 mg/L (two days per week) were equivalent to growth rates using a continuous 5 mg/L treatment. Conceivably, turbine releases with only 4 mg/L in conjunction with higher DO levels during periods of non-release may be biologically equivalent to exposure at a constant 5 mg/L level. Additional research on the effects of temperature and the length of exposure to mean and minimum DO concentrations could lead to the development of a practical growth rate model for rainbow trout.

Observations of fish during exposure to the lower DO concentrations of cyclic exposures include loss of natural color; increased ventilation rates; cessation of feeding; vomiting of food eaten as much as twelve hours earlier; and production of significant stress patterns in electrophoretic analyses of serum protein fractions for some species, but not all (Ref. 5-48, 5-44, and 5-49, TVA unpublished experimental results).

5.2 IMPLICATIONS FOR AGENCY REGULATIONS

Section 4 of this manual presents the most recent, generally recognized standards for dissolved oxygen, as published by EPA in April 1986. The 1986 report was the third report that considered dissolved oxygen standards since 1968 and reflected recent investigations and understandings of the effects of low DO concentrations on aquatic resources.

Under authorization of section 304(a)(1) of the Clean Water Act of 1977, the USEPA reviewed prevailing dissolved oxygen standards (Ref. 5-50) for protection of aquatic life, and following a non-regulatory scientific reassessment, issued newly revised biological standards (Ref. 5-2). USEPA revised earlier single-number DO standards based solely on mean concentrations, in favor of a two-number standard based on both minima and mean concentrations. This two-concentration standard and revised methods were adopted in recognition of several

concerns: the greater complexity of biological effects from low DO cannot be communicated by a single-number standard; the limited ability of mean DO standards to provide protection from acutely lethal DO concentrations; avoid underprotection of aquatic organisms exposed to extended periods of DO concentrations below 5 mg/L; minimize the cost to developers and action agencies of overly stringent standards; and, provide more guidance to users in judging applicability and appropriateness when modifying standards.

Historically, two basic approaches to establishing standards have been implemented. The first was a dynamic approach in which the standards varied with the ambient natural DO minima (Ref. 5-1), or with the DO needs of the fish, expressed as percent saturation (Ref. 5-3). The second approach (Ref. 5-50) maintained that a single minimum allowable concentration adequately protected the diversity of freshwater aquatic life. Both relied on minimum DO concentrations as the basis for the standards. Lack of data for naturally-occurring, site-specific minimum DO concentrations made application of the first approach extremely difficult. A more sophisticated, but relatively simple, two-tiered approach, including a minimum and average DO concentration, evolved from a review of DO standards for the Great Lakes (Ref. 5-51). Present EPA standards for DO are based upon this two-number method and is similar to national standards used for toxicants (Federal Register, 45 FR 79318).

The new standards were presented based on the dichotomous distinction between cold and warmwater species, life history stages, and lengths of exposure to low DO concentrations (Table 5-6). Application of coldwater standards is intended for salmonid populations or fish species having comparably greater sensitivity than most warmwater species. Determining the appropriateness of applying coldwater standards to non-salmonid species is left to the discretion and judgement of the states or other recommending agencies. Most states whose use-classification for a particular stream is for protection of fish and other aquatic life have adopted a 5 mg/L minimum concentration for non-salmonid waters and 6 mg/L dissolved oxygen minimum for salmonid streams. In some localities where species have been transplanted to warmer waters, maintenance of coldwater standards may be unattainable. Transplanted populations would certainly benefit if

Table 5-6

EPA DISSOLVED OXYGEN STANDARDS

A. Salmonid Waters:

a. Embryo and Larval Stages
- No Production Impairment = 11* (8)
- Slight Production Impairment = 9* (6)
- Moderate Production Impairment = 8* (5)
- Severe Production Impairment = 7* (4)
- Limit to Avoid Acute Mortality = 6* (3)

(* - Note: These are water column concentrations recommended to achieve the required intergravel DO concentrations shown in parenthesis. The 3 mg/L difference is discussed in the standards document.)

b. Other Life Stages
- No Production Impairment = 8
- Slight Production Impairment = 6
- Moderate Production Impairment = 5
- Severe Production Impairment = 4
- Limit to Avoid Acute Mortality = 3

B. Non-salmonid Waters:

a. Early Life Stages
- No Production Impairment = 6.5
- Slight Production Impairment = 5.5
- Moderate Production Impairment = 5
- Severe Production Impairment = 4.5
- Limit to Avoid Acute Mortality = 4

b. Other Life Stages
- No Production Impairment = 8
- Slight Production Impairment = 5
- Moderate Production Impairment = 4
- Severe Production Impairment = 3.5
- Limit to Avoid Acute Mortality = 3

C. Invertebrates:

- No production Impairment = 8
- Some Production Impairment = 5
- Acute Mortality Limit = 4

(Source: USEPA 1986, Ref. 5-2)

higher DO levels were met, but the constraint of having to meet the coldwater standards for non-native fish management and put-and-take fisheries was not the intent of the developers. Standards for life history stages were deemed necessary to address their often drastically differing sensitivities, as described in following sections, and apply only where and when those life stages occur.

Concentration standards for non-salmonid species were basically established to protect early life stages as sensitive as those of the channel catfish and other life stages as sensitive as those of the largemouth bass from production impairment. Impairment of fish production is essentially any reduction of fish growth rates (increase in biomass over time) or their attained weights when compared to that expected for fish growing under local ambient conditions for dissolved oxygen. The dissolved oxygen requirements of invertebrates were discussed, but for purposes of establishing new standards, itwas again "de facto" assumed that as long as lethal concentrations were avoided, protection of invertebrates would be afforded by maintenance of DO concentrations adequate to avoid impairment of fish production.

The selection of production impairment, though not the only possibility, as the "parameter of choice" for developing DO standards has many advantages, the major ones being that: the parameters are measurable under both field and laboratory conditions; assumptions relating laboratory and field data appear reasonable based on currently available data and knowledge; though limited in many cases, data is available, i.e. the three measurements affecting production (reproduction, survival and growth) are commonly investigated; and, this measure has economic and social ramifications.

Recommended ambient DO standards were established to protect the more sensitive fishes and appropriate life stages from damaging production impairment under annual "worst case" dissolved oxygen-high temperature conditions. These conditions typically occur for only a limited portion of the year at some hydroelectric sites. However, the standards are not considered as complete assurance against "no production impairment," particularly when minimal standards are maintained for extended periods of time. In areas where natural DO concentrations are less than 110% of applicable standards, minimum

acceptable DO concentration is 90% of the natural concentration (Ref. 5-2). Unless the degree of tolerance to low DO is known to be different for organisms present, no man-induced depression of DO concentrations below the 1-day minima should be allowed to occur. Concentrations below that level are in the identified, potentially lethal ranges for the applicable life stage and/or fishery (warmwater or coldwater).

For site-specific situations where DO patterns are extremely erratic, (i.e. where the 1-day minimum DO is appreciably less than the acceptable 7-day mean minimum or where significantly lower daily minimums occur in more than one or two weeks per year) it was recommended that either the occurrence of daily minima below the 7-day mean minimum be limited to three weeks per year, or that acceptable one-day minima for warmwater fisheries be increased to 3.5 mg/L and 4.5 mg/L for coldwater fisheries. Sample methods for calculations of appropriate mean DO concentrations were included in USEPA (Ref. 5-2). The biological significance of failure to maintain these recommended standards depends upon the duration of the event, the magnitude of the depression, the frequency of recurrence, the proportional area of the site failing to meet standards, and the biological importance of the site (Ref. 5-2).

5.3 REGIONAL FISHERY CONCERNS

To help establish the basis for the standards as they apply to the various species at specific sites, the following discussions present results of DO research for the more frequently encountered coldwater, coolwater, and warmwater fishes that are affected by hydropower discharges. The following information represents a thorough review of existing DO-related knowledge for these particular species. Non-inclusion of other fishes of regional concern reflects the lack of pertinent data concerning species-specific effects of DO levels on production. Fishes for which data is almost completely lacking include many important sport and commercial species such as the pink and chum salmon, cutthroat trout, blue catfish, white and yellow basses and sauger.

The discussions cover those species identified as important by canvassed state and federal natural resource agencies. As a result, species of concern are biased towards fishes of sport and commercial value. Some species of widespread distribution, (e.g. sunfishes, crappies, black basses and yellow perch) or of endangered status (e.g. snail darter or shortnose sturgeon), were not typically named as of primary regional concern in regards to DO effects, but may be of special site-specific importance.

First, to aid the hydro owner to initially identify the species that may be of concern at a particular location, the fish are grouped in a roughly geographical basis. Following the geographical groupings are detailed presentations of the research to date concerning each individual species. The studies should serve as a starting point for more in-depth considerations. For those seeking information that could pertain to site-specific standards, it should be pointed out that the majority of research has been conducted under laboratory conditions, under conditions not particularly representative of those typically found downstream of hydroelectric projects. Previous studies regarding fluctuating DO levels have usually considered drastic changes in DO rather than minor changes of 1 or 2 mg/L. TVA has conducted some studies in this area, and a more detailed description of the work is located in Appendix D. As a final word of encouragement, no amount of past research can refute the information gained from properly conducted studies at the site in question.

Geographic Representations

Northwest and Alaska. The salmonidae, comprised of widely ranging freshwater and anadromous fishes, is the dominant family of the northern coldwaters of North America, Europe and Asia. The five Pacific salmon (pink, chum, coho, sockeye, and chinook) of the genus Oncorhynchus naturally range in coastal areas and rivers from as far south as the Ventura River in California to as far north as the Mackenzie River in the Arctic Ocean. Certain species range far inland up the Mackenzie River and the Columbia River system of the Northwestern United States. Other salmonids such as the char, whitefish, ciscoes, grayling and other trout may be of site-specific concern within this region. Historically, no other fishes have contributed more to providing a stable food supply for settlement of

North America by both natives and Europeans. To the present day, these Northwestern species comprise one of the important exploited regional fisheries on earth, and, unfortunately, one of the most sensitive to any degradation of DO levels.

Southwest And Colorado River Basin. Within this drainage/region DO-related concerns appear confined to three species, i.e. two widely stocked salmonids, the rainbow and brown trout, and an endangered species extirpated throughout much of its former range, the Colorado squawfish. The oxygen requirements of the Colorado squawfish are unknown.

Great Lakes/North Central. The fishes of concern within the Great Lakes/North Central Region reflect the mixed cold/cool/warmwater faunal assemblages of the region. Recognition of the differing requirements of salmonid and non-salmonid groups of fishes was incorporated into DO standards development for the region by the International Joint Commission Great Lakes Water Quality Board (Ref. 5-52). Coldwater fishes of specific DO-related concern include the lake, brook, brown and rainbow trout (Salvelinus and Salmo), ciscoes (Coregonus) and whitefish (Prosopium and Coregonus). Coolwater species include the northern pike, walleye and smallmouth bass, and locally, warmwater fishes such as the largemouth bass and channel catfish may be of concern.

Northeast. Major species of concern of this region in regards to potential DO and other impacts relating to hydroelectric development include both anadromous coldwater salmonids and cool/warmwater non-salmonids. Denied access to spawning grounds by areas of low DO in the British Isles, the Atlantic salmon has experienced population problems in some drainages. Native to the North Atlantic basin, the classically anadromous Atlantic salmon ranges along the eastern coastal drainages of North America as far south as the Connecticut River, and inland along the St Lawrence River. The Atlantic salmon is world renowned as both a sport and commercial species. The American shad is another anadromous species of DO-related concern in this region. It ranges all along the eastern coast of North America from the St. Johns River of Florida to Newfoundland and Labrador. For inland fisheries, the black basses (Micropterus spp.), and brown,

rainbow and brook trout have been identified as most susceptible to DO problems within the region.

Central United States - Mississippi River Drainage (including Missouri, Ohio And Tennessee Rivers. Among the cool or warmwater fishes, primarily the smallmouth bass, the sauger, and sometimes the related walleye, provide highly prized sport fisheries both seasonally and year-round in many regulated tailwaters of the Ohio, Tennessee and Missouri Rivers. Within reservoirs experiencing DO-depletion, declining or cycling crappie populations are of resource agency concern within the region. Commercial species of concern in regards to low DO levels are ones such as the buffalos (Ictiobus spp.) and catfishes which may use deep-water areas of reservoirs as nurseries. Many artificially cold tailwaters existing below tributary dams throughout the central U.S. are managed as sport fisheries. In these cold tailwaters and downstream reservoirs, exotic and transplanted coldwater species, such as the rainbow, brown, brook and lake trout, are of concern to resource management agencies.

Southeast (exclusive of the Mississippi River drainage). Fishes potentially impacted by low DO within reservoirs and tailwaters of the Southeast are essentially warmwater or coolwater species including anadromous species such as the American shad and striped bass (also landlocked populations); resident fishes such as the crappies, sunfishes and black basses; and migratory freshwater fishes such as the sauger and white bass.

Species Accounts

Species selected for discussion were those for which adequate data was available for generalizations; those considered likely to be impacted by low DO because of their behavior, distribution, anadromous spawning behavior, or economic value; or were mentioned as species of concern by particular state resource agency representatives who were queried throughout the continental United States.

Salmonids (Coregonus, Oncorhynchus, Phosopium, Salmo, Salvelinus, and Stenodus). The family Salmonidae consists of seven genera: Coregonus, Oncorhynchus, Prosopium, Salmo, Salvelinus, Stenodus and Thymallus. Although there are other coldwater species and families,

development of national (Ref. 5-2) and regional (Ref. 5-52) DO standards has been based mostly on data from salmonids and coldwater standards have typically been applied by the states based on the presence of salmonid populations in affected waters.
Although extremely limited for some species, selected information related to potential production impairment by low dissolved oxygen is reviewed for all salmonid genera except Thymallus. Only that DO information likely to impair production is discussed. Known effects of fluctuating DO concentrations, relative sensitivities for species, exceptional species-specific information, and data which may be indicative of general family requirements, are highlighted within the species accounts. Preparation of this salmonid section has relied upon the reviews and summaries of oxygen requirements by Douderoff and Shumway (Ref. 5-53), NAS/NAE (Ref. 5-54), Davis (Ref. 5-3) and USEPA (Ref. 5-2), as well as the primary literature.

Lake Herring (Coregonus artedii):
Depletion of dissolved oxygen over spawning grounds has been suspected as a cause of mortality and crippling of coregonid fishes (Ref. 5-55 and Ref. 5-56). Brooke and Colby (Ref. 5-10) reported tests with eggs of the lake herring at four constant water temperatures and five constant dissolved oxygen levels. The optimum temperature for the highest percentage survival of fry decreased directly with the level of dissolved oxygen. The highest percentages of normal fry hatched at DO concentrations of 4 or 8, 2, and 1 mg/L DO were at 6, 4, and 2°C, respectively, indicating decreased DO need by embryos incubated at lower temperatures. At a temperature of 8°C survival was drastically reduced from 58% at 4 mg/L, to 11% and 0% at 2 and 1 mg/L, respectively. Constant DO levels below 4 mg/L at 6 to 8°C and below 2 mg/L at 2 to 4°C greatly increased the percentage of abnormal fry, and must be considered unsatisfactory for the successful development of lake herring embryos.

Mountain Whitefish (Prosopium williamsoni):
Siefert et al. (Ref. 5-37) reported effects of constant low DO on the survival and development of embryonic mountain whitefish. Survival of mountain whitefish was similar at 100% (12.3 mg/L) and 50% (6.5 mg/L) DO saturation at 4°C. A moderate reduction of survival was observed at 35% saturation (4.6 mg/L); severe reduction at 25%

saturation (3.3 mg/L) and no hatching occurred at 12.5% saturation (1.7 mg/L). Completion of hatching was delayed 15 to 17 days at 50% saturation and an additional 13 to 22 days at 35% saturation. All larvae at 35% saturation (4°C) and above began feeding within a day after hatching; but nearly all at 20% saturation died before or within a day of first feeding. No other information concerning effects of low DO on the genus Prosopium, was discovered.

Coho Salmon (Oncorhynchus kisutch):
Good survival for embryos of coho salmon to hatching has been observed at DO concentrations in the laboratory as low as 2.5 to 3.0 mg/L at 9 to 11°C (Ref. 5-6), with hatching being impossible only below 2.0 mg/L. Survival of coho at 7 and 10°C was reduced slightly in direct proportion to lowered DO levels in laboratory tests at 100, 50 and 25% air saturation (Ref. 5-9), and all embryos died at or prior to hatching at 12.5% saturation (1.4 mg/L). However, at these lower DO concentrations (Ref. 5-57, 5-9, and 5-6) deformed fry are more prevalent, alevins are smaller in size (mean weights being about one-fourth to one half that of embryos reared at levels near air saturation), and hatching is delayed (up to 11 days at 2.8 mg/L compared to most favorable DO levels). Again, as for other salmonids (Ref. 5-38), the toxicity of polluted effluent to juvenile coho increased at lower DO concentrations (Ref. 5-58) causing increased mortality.

In general, Warren et al. (Ref. 5-6) found that the growth rate of juvenile coho salmon held for 13-20 days on unrestricted rations was dependent upon DO concentration and was depressed at all reduced levels (between approximately 3 and 12 mg/L) below air saturation and at all temperatures tested (between 8.6 and 21.8°C). In one series of tests at 18 and 20°C the growth (wet weight) of coho salmon was reduced an average 8, 17, and 42 (30 at 18°C) percent at DO levels of 5, 4, and 3 mg/L DO when compared to those reared at about 9 mg/L. When compared to that shown by juveniles reared at 8.3 mg/L, growth of juvenile coho (Ref. 5-59) declined slightly at 5 or 6 mg/L and more sharply at DO levels reduced further below; food conversion ratios were markedly depressed below 4 mg/L; and mortality was high at 2.1-2.3 mg/L with surviving fish consuming little food and lost weight. Fisher (Ref. 5-42) reported marked reductions in growth for

juvenile coho held at all continuous exposure DO concentrations below saturation (9.5 mg/L). But Thatcher (Ref. 5-60) reported that at 3, 5 and 8 mg/L at 15°C and a range of food consumption rates, significant growth reductions occurred only at 3 mg/L and food consumption rates greater than 70%. Trout at 5 mg/L did, however, spend less energy in swimming activity, which under natural conditions could restrict foraging. The work of Warren et al. (Ref. 5-6) and Thatcher (Ref. 5-60) indicates that growth impairment by low dissolved oxygen appears to be a function of lower food intake. Davison et al. (Ref. 5-61) observed that juvenile coho salmon at 2.9 mg/L and 20°C fed well and gained weight, but concluded that their fish were "probably somewhat affected."

Fisher (Ref. 5-42) indicated that wide fluctuations in DO per se do not greatly impair growth of salmon in the absence of adverse low DO concentrations near or at the nadir of the diurnal cycle. However, exposure to equal periods of nonlethal low DO at 2.3 and 3.0 mg/L and high dissolved oxygen levels at 9.6 and 9.5 mg/L, respectively impaired growth almost as greatly as if fish were exposed to the equivalent continuously maintained lowest DO level.

Activity level does have different effects at different oxygen concentrations. Hutchins (Ref. 5-62) reported growth rate reductions of 20 and 65% at 3 mg/L for coho held at current velocities of 8.5 and 20 cm/sec. At 5 mg/L DO, a 15% reduction occurred at the higher velocity, but no reduction was observed at the lower velocity. For juvenile coho, maximum sustained swimming speeds in the range of 30 to 45 cm/sec were reduced by 8.4, 12.7 and 19.9% at DO concentrations of 6, 5 and 4 mg/L, respectively (Ref. 5-63), and Dahlberg et al. (Ref. 5-23) reported reduced maximum swimming speeds for coho at all DO levels below saturation. Hermann (Ref. 5-64) concluded that DO concentrations to which juvenile coho salmon may be exposed for long periods of time without drastically affecting growth, feeding, food conversion and activity level, lies within the range of 4 to 6 mg/L. Katz et al. (Ref. 5-22) and Warren et al. (Ref. 5-6) reported that at 20°C, juvenile coho were able to swim for 24-hours at DO concentrations of 3 mg/L and above at swimming speeds between 2 and 4 cm/sec.

In the laboratory (Ref. 5-19), coho salmon showed a strong preference for DO concentrations of 9 mg/L over those near 1.5 mg/L; moderate selection against 3.0 mg/L; and detectable selection against 4.5 and 6.0 mg/L.

Koski (Ref. 5-33) evaluated the differences between DO concentrations in overpassing waters and that occurring intergravelly within coho salmon redds. As measured over several months, the average intergravel DO concentration within the redds was about 2 mg/L, and the minimum DO concentrations 3 mg/L lower than those of the overpassing lows. Thus the DO exposure concentrations for developing embryos and larvae under natural conditions should be considered to be at these lower intergravel levels.

Sockeye Salmon (Oncorhynchus nerka):
Newly hatched alevins of sockeye salmon incubated at continuous 3.0 or 6.0 mg/L DO showed less yolk utilization, retarded development of fins and pigmentation, and were smaller in size than those incubated at 11.9 mg/L DO (Ref. 5-31). Developmental retardation was even greater between hatching and absorption of the yolk sac. Alevins incubated in 3.0 mg/L DO required two weeks longer than those held at 6.0 mg/L, and three weeks longer than those held at 11.9 mg/L to completely absorb the yolk and reach the fry stage. Large differences in growth were observed for alevins reared at the different DO levels. Alevins reared at 3.0 or 6.0 mg/L DO consistently weighed less than those reared at 11.9 mg/L DO. The end result of these developmental delays and growth reductions is the production of small, less developed alevins with less chance of survival, particularly if emergence must be correlated with some physical environmental cycle.

Field examinations of sockeye redds where DO levels were as low as 3.0 mg/L, however, determined that some embryos did hatch and have some unquantified survival (Ref. 5-31). Klyashtorin (Ref. 5-65) reported young sockeye living continuously in a small spring-fed creek at 2.4 mg/L DO (30% saturation) at 8.5°C. Though both development and growth were adversely affected at these DO levels, no effect on mortality was observed.

Steelhead and Rainbow Trout (Oncorhynchus mykiss = Salmo gairdneri): McNeil (Ref. 5-66) observed 50 to 70 percent mortality of juvenile steel head trout at DO concentrations averaging 1.6-1.7 mg/L (16-20°C) in late spring and early summer, and Silver, et al. (Ref. 5-67) reported 100 percent mortality of steelhead embryos held at 1.6 mg/L (9.5°C). In tests at higher DO concentrations from 2.6 to 11.2 mg/L DO, survival was unaffected by DO. Survival of larvae at low DO concentrations was apparently possible by reduction of growth and development rates, yielding smaller, weaker fry that survived under laboratory conditions. Sowden and Power (Ref. 5-68) reported no survival of embryos in redds of rainbow trout where mean DO was less than 4.3 mg/L and negligible survival (<1.0%) at 5.2 mg/L and below. Survival was not over 10% until mean DO levels in redds were above 5.8 mg/L. Phillips and Campbell (Ref. 5-69) reared embryos of steelhead trout in containers placed in stream bed gravel at different locations. Few or no sac larvae were recovered from containers where the mean DO concentration was below 8 mg/L. This study suggests that embryos or newly hatched fry reared at even moderately reduced DO concentrations may not survive well in nature.

Mortality of rainbow trout and many other fishes, due to an array of toxic poisons, is also increased at lower dissolved oxygen levels (Ref. 5-70, 5-71, and 5-32). This phenomenon is probably due to the fish increasing the passage of water over the gills in response to lowered DO, thus increasing the amount of poison reaching gill epithelia, where most poisons are absorbed.

Steelhead alevins reared at 5 or 3 mg/L DO (Ref. 5-32) had weights reduced by 5.5 and 9.1 percent, respectively, when compared to those reared at 10 mg/L DO. Shumway et al. (Ref. 5-57) observed reduced size at hatching of fry reared at low and intermediate DO levels between 2.5 and 11.5 mg/L, when compared to those reared at air saturation. Structurally abnormal alevins were produced at DO concentrations of 1.6-2.6 mg/L (Ref. 5-67), but had survived to the hatching stage.

Reduction in sport fishery harvest rate of rainbow trout in Lake Taneycomo, Missouri was hypothesized to be related to decrease of minimum daily DO concentrations below 6 mg/L (Ref. 5-30). Reduction

of DO levels from 6 mg/L to 5, 4, and 3 mg/L appears to reduce the harvest rate 20, 40 and 60 percent, respectively, probably as a result of decreased feeding activity. This hypothesis is in agreement with the findings of Warren et al. (Ref. 5-6) and Thatcher (Ref. 5-60) for coho salmon that growth impairment by low DO appears to be a function of decreased feeding activity. Over a ten year period, annual cycling of LeCren condition of rainbow trout fingerlings in a tailwater in Tennessee, where tailrace DO levels historically fell as low as 0.6 mg/L, was found to be statistically in direct relation with DO concentrations in tailrace discharges (Ref. 5-72).

The distribution of rainbow trout and their susceptibility to fishing mortality in exploited fisheries can be altered by low DO levels. Heimer (Ref. 5-73) found that catch rate of planted rainbow trout in American Falls reservoir on Snake River of Idaho was highest during periods of low DO. This occurrence of increased catch rate was attributed to avoidance of low DO concentrations and high temperatures and increased numbers of fish in areas of more suitable oxygen and temperature levels. Serns (Ref. 5-74) found that vertical movement of rainbow trout across a severely DO-depleted 6-m strata, either from or into an artificially aerated hypolimnion was not restricted. Planted rainbow trout were maintained year-round in an Ohio quarry with a hypolimnion artificially aerated to 7-8 mg/L (Ref. 5-75), where the fishery previously died out each summer during the thermal stratification period when hypolimnetic DO depletion was severe.

Maximum swimming speeds of rainbow trout at DO concentrations of 5.1 mg/L (14°C) and 3.8 mg/L (22°C) were reduced 30 and 43 percent, respectively (Ref. 5-76). As stated by USEPA (Ref. 5-2), the significance of lower DO levels to swimming depends upon the level of swimming performance required for the survival, growth and reproduction of a fish. Failure to elude predation or negotiate a rapids along a spawning migration route may be considered an indirect lethal effect. However, moderate levels of swimming activity required by rainbow trout and salmonids in general are not significantly affected by DO concentrations that are otherwise at acceptable levels for reproduction and growth.

Chinook Salmon (Oncorhynchus tshawytscha):

Effects of hypoxia on development of chinook salmon demonstrated in the laboratory, produce smaller, weaker alevins which could not be expected to survive under natural conditions. Embryos of chinook salmon held from fertilization to hatching do not survive DO concentrations of 1.6 mg/L at 11°C under laboratory conditions (Ref. 5-67). Although large percentages of embryos (92.3-100%) survived to hatching at all DO levels from 11.7 mg/L to as low as 2.5 mg/L, reduction of growth and retardation of developmental rates occurred for all reduced DO levels. Hatching was progressively delayed at all reduced DO concentrations below 11.7 mg/L. Size of alevins at hatching was directly dependent upon DO levels for all concentrations up to near 11.7 mg/L. Comparable results were reported by Eddy (Ref. 5-77) at a similar temperature. Entire populations of trout fry may be affected adversely by developmental delays if time of hatching is coordinated with other environmental occurrences such as plankton blooms or insect emergence. Speculation as to the effect or non-effect of alevin hatching size has been made (Ref. 5-77), since by yolk absorption most surviving fry reach a similar size for that species (Ref. 5-31, 5-53, and 5-78), no matter at what DO concentration they were reared, but factual field studies are lacking.

Reduction of DO to 3.5 mg/L at 10.5°C had little or no effect on survival of embryos and fry (Ref. 5-77). However, at higher temperatures, 12.0°C and 13.5°C, reductions in DO concentration resulted in moderate or substantial increases in mortality, respectively.

Temperature and water velocity may have synergistic effects with DO on growth of chinook salmon. For example, growth of young chinook was relatively unaffected by 5 mg/L DO at 13°C, but was reduced 34% at 20°C (Ref. 5-6). In experiments conducted at 21.7, 18.6 and 17.8°C, growth rates of chinook were dependent on DO concentration at all levels below air saturation. At 13.2, 13.0 and 8.4°C, however little or no dependence on DO level was observed. Thus the detrimental effects of low DO are exacerbated at higher temperatures and estimates of production impairment on growth taken from data collected at lower temperatures would grossly underestimate effects at these higher temperatures. In regards to water velocity, chinook salmon embryos reared at a DO concentration of 11.7 mg/L and water velocity of 92 cm/hr were larger than those reared at 5.6 and 8.0 mg/L even at

water velocities as high as 1,350 cm/hr (Ref. 5-67). At 3 mg/L reduction of water velocity from 100 to 10 cm/hr produced greatly increased mortality of chinook alevins (Ref. 5-1). The velocity of water required for normal development of chinook embryos in redds is then much less if DO concentrations are high.

Chinook strongly prefer DO levels of 9 mg/L or greater and show strong selection against 3 mg/L DO and lower (Ref. 5-19). Upstream spawning migrations of chinook may be disrupted by low concentrations of DO. An 11 year study indicated that upstream passage of chinook salmon and coho salmon through a fish pass was apparently inhibited by DO levels below 5 mg/L (Ref. 5-79). One important factor in design of some fish passage devices is the attainable swimming speed of the fish to be passed. Maximum attainable swimming speeds may be affected by DO level. Reduction of DO from air saturation levels to 7, 6, 5, 4 and 3 mg/L resulted in reductions of maximum sustained swimming speed of 10, 14, 20, 27, and 38 percent, respectively (Ref. 5-63). Katz et al. (Ref. 5-22) reported chinook salmon able to swim for 24-hours at 2 to 4 cm/sec and DO concentrations of 3 mg/L and above.

Atlantic Salmon (Salmo salar):
Data on the relatively high dissolved oxygen requirements for the Atlantic salmon indicate the need for maintenance of stringent water quality standards for oxygen levels in rivers utilized by this species. For the anadromous Atlantic salmon, DO depletion in estuaries and lower reaches of rivers is a critical factor in affecting accessibility of spawning areas to these fishes. In the Thames estuary of the United Kingdom, Alabaster and Gough (Ref. 5-80) found that successful passage of salmon can be achieved over short (1 km) distances with median DO concentrations as low as 3.5 mg/L; increasing to 3.8 mg/L and 4.3 mg/L for greater distances (10 km and 30 km, respectively). In a survey of estuaries of the United Kingdom, Hugman et al. (Ref. 5-81) concluded that, in the absence of toxicants, a minimum of 5 mg/L would allow passage of migratory salmonids in most cases and 3 mg/L would allow establishment of a more restricted fishery. Mass mortalities of adult Atlantic salmon occurred in the Rivers Wye and Don at DO concentrations of 0.5 mg/L (Ref. 5-162) and about 4.0 mg/L (Ref. 5-79), respectively.

In acute tests, the median lethal threshold for Atlantic salmon smolts is about 3.3 mg/L in freshwater and 2.6 mg/L in 30-80% seawater (Ref. 5-82). Acclimation to low DO does extend survival of smolts and reduces mortality slightly. In a longer-term 16 week test (Ref. 5-83) rearing young Atlantic salmon in jars and troughs, however, mortality increased when DO dropped to less than 6.5 mg/L. Hamor and Garside (Ref. 5-84, 5-85, and 5-86) found that survival and developmental rate increased directly with increasing DO and that survival during embryogenesis and the hatching period was limited primarily by DO concentration. Retarding effects of low DO on embryonic growth, decreasing efficiency of yolk utilization, became progressively stronger after the first 10% of embryonic development. This effect is related to increasing oxygen requirements by differentiating tissues and organs. Nikiforov (Ref. 5-87) also reported better growth and complete yolk absorption in 5-day-old salmon reared for 25 days at 6.8-7.5 mg/L DO, as compared to those reared at 4.5-5.0 mg/L which weighed less than one-half as much and retained one-third of their yolk.

Larval Atlantic salmon were unable to detect or avoid low DO concentrations, but older fry 6 to 16 weeks of age strongly avoided low DO concentrations up to 4 mg/L (Ref. 5-21). The critical oxygen concentration for Atlantic salmon, as measured by ability to resist a current of 55 cm/sec, is about 4.5 mg/L, in comparison to 2.0 mg/L for rainbow trout and 1.7 mg/L for goldfish (Ref. 5-88). Differences in oxygen consumption rates induced by photoperiod manipulation for post-smolt salmon (Ref. 5-89) demonstrates that salmon may seasonally have varying DO requirements.

Brown Trout (Salmo trutta):
Little is known of specific effects of low DO on brown trout. Neither a comprehensive field nor laboratory investigation on effects of low DO on brown trout has been conducted. Witzel and McCrimmon (Ref. 5-90) reported brown trout spawning at DO saturations of 83-100%. A highly successful trophy trout fishery below Norris reservoir in Tennessee began in 1980, and has produced the state record for brown trout in 1988, despite dissolved oxygen levels that annually fall as low as 3 mg/L in the tailrace.

Young brown trout 6-26 weeks of age showed marked avoidance of DO concentrations up to 4 mg/L (Ref. 5-21); those younger were unable to detect or avoid low concentrations of DO. Growth rate of brown trout appears unaffected (Ref. 5-91) by reduced DO down to 50% saturation (5 mg/L at 16°C). In a study reusing waters for rearing brown trout where DO levels were between 3.6 and 7.6 mg/L, growth began to decline and mortality increased when DO averaged 4.8 mg/L (Ref. 5-92) or lower.

Brook or Speckled Trout (Salvelinus fontinalis):
Brook trout appear particularly sensitive to low DO concentrations. In a range from 3.7 to 10.5 mg/L, survival of brook trout embryos was directly related to dissolved oxygen concentration (Ref. 5-34). Survival of embryos and larvae of brook trout (Ref. 5-9) was high at DO saturations of 25% (2.9 mg/L) and higher; markedly reduced at 20% (2.3 mg/L); and all fish died at 12.5% (1.6 mg/L) before they began feeding. No brook trout survived a 10-hour exposure at or below 1.5 mg/L DO at 10°C (Ref. 5-7) and mortality occurred in less than 1-hour at 1.2 mg/L. For brook trout, the difference between DO concentrations causing total mortality and those causing no mortality is only about 0.5 mg/L, when the exposure level is less than a week. At 10°C, 1.1 mg/L DO killed all brook trout in less than 3.5-hours; 1.3 mg/L caused complete mortality in less than 3.5 days; and all trout survived 1.9 mg/L for 3.5 days (Ref. 5-12). For the 3.5 day test at 20°C, all trout died at 2.4 mg/L and the corresponding no mortality level was 2.7 mg/L. Brook trout held at DO concentrations just above incipient lethal levels (1.75-1.9 mg/L, Ref. 5-7) were sluggish in movements, fed poorly and were susceptible to disease.

Growth of brook trout exposed to DO concentrations allowed to fluctuate as low as either 2.4 mg/L or 3.5 mg/L was adversely affected (Ref. 5-93) when compared to that of fish maintained near a constant 10.6 mg/L. In trials where fluctuations in DO were limited to between absolute values of 6.5 and 10.6 mg/L, growth was not affected.

In a study in Pennsylvania (Ref. 5-34) where brook trout were not spawning in areas of groundwater upwelling, mean DO concentrations in redds averaged from 2.1 to 3.7 mg/L less than the overpassing surface

water. Year to year variation indicated that greater intergravel DO depletion occurred under low flow conditions. Year to year variation suggested low flow conditions exacerbate intergravel DO depletion. Since brook trout in most streams prefer to spawn in areas of groundwater upwelling (Ref. 5-90), DO concentrations in redds are typically controlled by ambient DO rather than anthropogenic influences.

Lake Trout (Salvelinus namaycush):
Garside (Ref. 5-94) investigated the effects of temperature and low DO on development of lake trout embryos exposed to DO levels of 2.5, 3.5, 4.5 and 10.5 mg/L at 2.5, 5.0, 7.5 and 10.0°C. In all cases embryos reared at the three reduced DO concentrations were delayed in development and hatching when compared to controls, had lengthened hatching periods, reduced vitelline circulatory structures (important in larval oxygen transport), and abnormalities of the head and trunk. Though Garside did not report survival, all these factors potentially reduce the success of hatching and survival.

Carlson and Siefert (Ref. 5-35) did report survival and development of lake trout from fertilization through first feeding as being adversely affected or inhibited at all reduced oxygen saturations tested (50% and lower, 6 mg/L). Survival was adversely affected at all reduced concentrations, although only slightly at 50% saturation (7°C). At 20% saturation (2.4 mg/L only a few embryos survived to hatching. Other effects at reduced DO concentrations included delay of initial hatch by 2-5 days, delay of first feeding 7-29 days, and reduction of fish length by 1.7-2.7 mm. Soderberg and Krise (Ref. 5-95) found no DO effects on growth or survival for caged sub-adult lake trout reared at a DO concentration of 8 mg/L.

Field-derived information on low dissolved oxygen effects on lake trout is meager. For the two years following introduction of lake trout in Norris Lake in Tennessee, sub-adult trout underwent dam passage into the tailwater in the autumn only following lake turnover, even though generation schedules and discharge were similar prior to and following turnover. Norris reservoir is a strongly stratifying, hypolimnetic release dam that suffers severe oxygen depletion in the lower water column. The vertical distribution of lake trout within the reservoir was thus probably affected, forcing

lake trout upward into warmer, less than optimal temperature, waters. The state stocking program was discontinued after two years due to no harvest of lake trout in the reservoir creel.

Non-Salmonids.

Northern Pike (Esox lucius) - coolwater:

Dissolved oxygen concentration is most often the most important habitat variable affecting overwinter survival of adult northern pike. Shallow, heavily weeded impoundments and rivers with low discharges are habitats favorable for northern pike most of the year. In winter however, these habitats frequently develop very low dissolved oxygen concentrations. Laboratory and field observations indicate the northern pike is more tolerant of low DO conditions during the winter than many other coolwater or warmwater species. Under conditions of gradually decreasing DO, northern pike are able to tolerate winter concentrations as low as 0.1 to 0.4 mg/L for at least several days (Ref. 5-96, 5-97, and 5-98). Prolonged winter DO concentrations of less than 1.0 mg/L however, cause partial or complete winterkills (Ref. 5-99 and 5-100). As temperature increases, DO requirements increase exponentially, but the lower incipient lethal concentration (Concentration below which pike cannot survive for an indefinite time) (Ref. 5-101) is relatively low, being less than 1.5 mg/L at 28°C (Ref. 5-102).

Though not quantified, tolerance of low DO appears to be inversely related to size for juvenile and adult northern pike in natural habitats. In an Ontario lake with low DO levels, winter mortality was 100% for pike older than 2 years and/or greater than 39 cm fork length, but many younger individuals survived (Ref. 5-103). Also, in a Montana stream where winter DO decreased to low levels, very few northern pike older than 2 years were present, although young fish were common (Ref. 5-104).

Tolerance to low DO concentrations decreases from embryonic to larval stages of the northern pike (Ref. 5-105). "In situ" experiments of up to 8-hours duration, conducted at natural spawning sites, showed that 0.6 mg/L DO produced no mortality of embryos but 100% mortality of sac-larvae and larvae of northern pike. Complete larval mortality also occurred at 1.6 mg/L, but no mortality at 4.0 mg/L in 8-hour tests. Exposure of larvae to 0.8 mg/L DO for a little as 2-hours

also greatly reduced survival. Thus, larval northern pike appear to tolerate 4 mg/L for at least short durations. This level is further corroborated in a laboratory study by Siefert et al. (Ref. 5-106). Upon observing the greater number of deaths at beginning of feeding at low (33% saturation, 3.2 to 3.3 mg/L) DO levels, Siefert et al. (1973) concluded that larvae could probably hatch and survive for a few days at saturations as low as 33%, but that survival would not at all be assured once feeding had begun. A DO level of 50% saturation (about 4.9 mg/L at 15-19°C) appeared to be sufficient for the survival and development of northern pike.

When held 20 to 24-hours at DO concentrations less than 6 mg/L and 21 to 22°C, young of the year (12 to 38 g) pike showed distinct signs of stress (Ref. 5-107). Feeding ceased at 2 mg/L and no test fish survived more than 20-hours at 1.0 mg/L.

In laboratory chambers, dissolved oxygen concentrations below 7 mg/L (77% saturation) reduced growth rates of juvenile northern pike at 18.6°C and a flow rate of 0.24 ml/sec (Ref. 5-108). Test DO levels were 7.2, 6.0, 5.4, 2.9, 2.6, and 1.7 mg/L. A decline in growth was gradual down to concentrations of 3 to 4 mg/L (33 to 44% saturation) and drastic at levels below 3 mg/L. At 5.4 mg/L, growth reduction was 5% after 6 to 7 weeks, whereas at 1.7 and 2.6 mg/L, growth reduction was about 65%.

Cyprinids: Fathead Minnows (Pimephales), Carp (Cyprinus carpio) and Goldfish (Carasius auratus):

The three cyprinid species covered herein are those for which most DO information is available. Most life stages of these species are tolerant of low DO levels and are undoubtedly unrepresentative of typical DO requirements for a large percentage of the species in the family Cyprinidae. This family includes a large number of species which dwell in riffles or runs, habitats typically high in dissolved oxygen concentrations.

Adult and juvenile carp are very tolerant of low dissolved oxygen, a condition of many of the warm, fertile waters where carp are often found (Ref. 5-109, 5-110, and 5-111). Hover (Ref. 5-112) reported carp feeding in an oxygen-depleted hypolimnion at DO concentrations

less than 2 mg/L. Adult carp gulp air when the DO is 0.5 mg/L or less (Ref. 5-113).

Lethal DO concentrations (50% mortality) of constant 1 day exposure for carp are 0.4 to 0.8 mg/L at 10 and 20°C, respectively; and for 7-day exposures, 0.4, 1.2 and 2.8 mg/L at 10, 16, and 20°C, respectively (Ref. 5-12). Lower lethal oxygen levels reported for fry held in the laboratory are less than 1.6 mg/L (between 0.2 and 1.6 mg/L) at 21 to 22°C (Ref. 5-1 and 5-114). At temperatures less than 20°C, the lower lethal oxygen levels for carp juveniles is less than 1 mg/L (Ref. 5-115 and 5-12). However, the growth rate of juveniles begins to decrease at approximately 2.1 mg/L at 20 to 23°C (Ref. 5-116). For the goldfish and fathead minnow, declining DO values less than 2 mg/L caused mortality (Ref. 5-117 and 5-118 respectively).

Carp eggs are not tolerant of low oxygen levels, but minimal (4%) survival has been reported (Ref. 5-119) for short exposures to DO concentrations as low as 1.2 mg/L at 25°C. Hatching success increases with increasing DO. Kaur and Toor also reported 40% hatching success at 3 mg/L; 65% at 6 mg/L; and 92% at 9 mg/L DO, and stated that DO levels below 6 mg/L appeared inadequate for proper survival of carp embryos to hatching.

Critical concentrations (see largemouth bass section for definition) identified for the carp were 3.4 and 2.9 mg/L DO at 10 and 20°C, respectively (Ref. 5-120). Respiration becomes elevated (Ref. 5-121 and 5-3) at or below 3 to 5 mg/L (13 and 23°C, respectively). For goldfish, critical concentrations were 1.8 and 3.5 mg/L DO at 10 and 20°C, respectively. Barr et al. (Ref. 5-122) found that acclimation of goldfish to low DO concentrations affected their oxygen consumption and standard metabolism. As possibly occurs with many fish, acclimation rate and timing may thus affect the physiological needs of fish for maintenance of normal activities such as feeding. This factor could have large ramifications for impairment of production for species of fish either intermittently or daily exposed to widely fluctuating DO levels in tailwaters. In general, critical concentrations for cyprinids fall between 2 and 4 mg/L with higher temperatures correlated with higher critical DO levels. However, USEPA (Ref. 5-2) critically evaluated the data of Beamish (Ref. 5-120) and

suggested that, as indicated by increased ventilation rather than decrease in oxygen consumption, the first signs of hypoxic stress were at even higher DO levels (4.2 and 5.8 mg/L DO at 10 and 20°C, respectively) than previously reported for the carp.

Chronic effects of continuous low DO at several concentrations on the life cycle of the fathead minnow were thoroughly investigated by Brungs (Ref. 5-17). Spawning did not occur at 1 mg/L; number of eggs produced per female was reduced at 2 mg/L, but not at higher concentrations; and where spawning occurred, the percentage hatch of eggs (81-89%) was not affected when the larvae were exposed to the same concentration as their parents. With decreasing DO, incubation period increased from the normal 5 days to 8 days. Mean larval survival was 6% at 3 mg/L, 25% at 4 mg/L, 66% at 5 mg/L, and 50% in controls. Survival of larvae was thus directly proportional to DO concentration. Mean growth of surviving larvae at 5 mg/L was about 20% less than that of controls, but whether or not density-dependence was a factor is not known. Though commonly used in toxicity testing the effects of fluctuating DO concentrations on this species are not known.

Channel Catfish (Ictalurus punctatus) - warmwater:
Channel catfish are a ubiquitous species occurring in reservoirs, and rivers, as well as warm, cool and even cold tailwaters throughout the United States. Within lakes, the distribution of channel catfish may be markedly affected by DO concentrations related to stratification. Within a small lake in Kansas (Ref. 5-123) where DO was nil at the 4-meter depth, channel catfish were confined (89%) to the upper 3-meter of the water column. When stratification was prevented and the DO concentration was greater than 4 mg/L throughout the water column, 64% of the fish were located below the 3-meter isopleth. DO levels of 5 mg/L appear marginally adequate for growth and survival of channel catfish (Ref. 5-124), but DO concentrations greater than 7 mg/L are optimum. Below 5 mg/L feeding is reduced (Ref. 5-125).

Exposure to low DO significantly reduces growth of fingerling channel catfish. After a 6 week exposure and maximal feeding, channel catfish reared at 60% (5 mg/L) DO saturation showed 22% less weight gain than those reared at 100% (8 mg/L) saturation (Ref. 5-126). On

lower rations for 14 weeks, channel catfish growth was reduced only at the 36% (3 mg/L) saturation level. At this DO concentration, fish were noticeably lethargic and fed poorly. In long-term (up to 177 days) studies exposing catfish to different DO levels, Raible (Ref. 5-127) found a gradual reduction in growth at each decreasing concentration below 6 mg/L. For each mg/L increase in DO between 3 and 6 mg/L, he calculated a 10 to 13% increase in growth. When compared with control fish over a 10 week test period (Ref. 5-45), weight gain of catfish was reduced by 14, 39 and 54% at DO concentrations of 5.0, 3.4 and 2.1, respectively. Growth rates were reduced 5, 18 and 23%, respectively.

The embryonic and larval stages of the channel catfish, along with the walleye, northern pike and smallmouth bass, are more sensitive to low DO concentrations than those of most other cool and warmwater fishes. Reduced DO concentrations lighten pigmentation, extend incubation periods, delay feeding, and reduce early growth of channel catfish (Ref. 5-128). During 2 or 3 week exposures at 25°C, survival of embryos and larvae of channel catfish was slightly reduced at 5 mg/L and significantly reduced at 4.2 mg/L. At a slightly higher temperature (28°C), survival was reduced at 3.8, 4.6 and 5.4 mg/L. Total mortality occurred at 2.3 mg/L.

Striped Bass (Morone saxatilus) - warmwater:
Field observations and experimental results indicate that in both fresh water and estuaries, striped bass become physiologically stressed as DO concentrations decrease to about 3 mg/L. Concentrations of 2 mg/L DO are uninhabitable for striped bass. Chittenden (Ref. 5-24 and 5-25), working in Delaware Bay, found that the distribution of striped bass was bounded by the 3 mg/L isopleth. Cheek et al. (Ref. 5-129) observed progressive limitation of striped bass in a reservoir to areas where temperatures were less than 24°C and DO was greater than 4 mg/L. Talbot (Ref. 5-130) suggested 4 mg/L DO was too low for successful reproduction of striped bass. But striped bass appear to have the ability to somewhat tolerate DO conditions (Ref. 5-131 and 5-132) marginal for many other species of fish.

The performance of striped bass under conditions of low DO concentrations has been defined experimentally in several investigations.

Krouse (Ref. 5-133) concluded that striped bass could survive DO concentrations of 3 mg/L in the 13 to 25°C range of temperatures, but not at 1 mg/L. Turner and Farley (Ref. 5-134) observed a reduction in survival of both eggs and larvae after eggs were exposed to 4 or 5 mg/L DO concentrations when compared to those hatched at saturation. As time of exposure to low DO increased from 6 to 30-hours, mortality of eggs and larvae increased. Dorfman and Westman (Ref. 5-135) observed 80% survival of striped bass juveniles transferred from ambient levels of DO to 2 (20°C) or 3 mg/L (25.6°C). Juvenile striped bass acclimated to 18°C (Ref. 5-136), avoided DO concentrations of 3.8-4.0 mg/L in experimental gradients. Appetite is affected adversely at low dissolved oxygen levels (Ref. 5-137). As DO levels were lowered, Chittenden (Ref. 5-25) documented "restlessness" at 3 mg/L (16-19°C), with inactivity, loss of equilibrium and death occurring at lower concentrations. Ventilation rate was maximum at 2-3 mg/L but declined at lower DO concentrations.

Striped bass are most often thought of as reservoir or anadromous estuarine fishes, but they will often leave warm de-oxygenated reservoirs and, seeking both acceptable thermal and oxygen refugia, move into cooler, more oxygenated waters of mainstream reservoir tailwaters or spring-fed waters. Within some reservoirs, as summer epilimnetic temperatures rise above thermal tolerances and hypolimnetic oxygen depletion expands, a temperature-oxygen "squeeze" causes mortalities in some populations of larger adult striped bass (Ref. 5-26). In one instructive field study (Ref. 5-138), radio and thermistor-tagged adults made repeated attempts to find habitat with acceptable temperature and oxygen levels by rapidly moving between shallow depths with suitable DO but too-high temperatures (> 25°C), to cooler (23-24°C) but oxygen-deficient depths. Fish consistently turned back toward the surface when encountering DO levels in the 0.5 to 2.5 mg/L range.

Sunfish (Lepomis spp.) - warmwater:
Other than for the adult bluegill, very little is known about the dissolved oxygen requirements for other species and life stages of warmwater sunfishes. Bluegills can tolerate dissolved oxygen levels below 1 mg/L for short durations (Ref. 5-139, 5-96, 5-11, 5-98), but adults showed considerable avoidance of 1.5 to 3 mg/L DO (Ref. 5-19)

in "channeled avoidance tanks." No avoidance of 4.5 mg/L was observed. The first external signs of stress occurs as DO levels approach 5 mg/L; at 3 mg/L bluegills intermittently swim to the surface; and at 1 mg/L feeding ceases (Ref. 5-107). Critical levels (see largemouth bass section for definition) of dissolved oxygen for bluegill are 0.75 to 1.5 mg/L at 25°C and 2.0 mg/L at 35°C (Ref. 5-11). No adverse effects on growth, survival or distribution pattern have been documented when DO levels have exceeded 5.0 mg/L (Ref. 5-44 and 5-107).

Early life stages of bluegill are more hardy than smallmouth bass with respect to toleration of low DO. In tests (Ref. 5-105) found that a 4-hour exposure to 0.5 mg/L caused no mortality of embryonic stages, but was lethal to sac-larvae. Sac-larvae did survive similar exposures to 1.8 mg/L DO. However the larval stage, probably the most DO sensitive life stage, was not tested.

Adult warmouth sunfish are extremely tolerant of low DO conditions of short duration, being among the last species to die when subjected to low DO (Ref. 5-140). Warmouth survived concentrations under laboratory conditions of 0.3 (Ref. 5-140) to 1.0 mg/L (Ref. 5-141), and in a lake where access to the surface was possible, down to 0.7 to 1.3 mg/L DO (Ref. 5-139). However, based on oxygen consumption rate experiments (Ref. 5-140), the critical DO level for long-term survival is 3.6 mg/L. Dissolved oxygen requirements for other life stages are unknown.

Periodic low DO may exacerbate the toxic effects of other substances (Ref. 5-142) upon sunfish such as the bluegill, but little is known about such synergistic effects. Cairns and Scheier (Ref. 5-143) observed decreased tolerance to toxic substances in fish exposed to DO declining from saturation for 3-hours, held at 2 mg/L for 2-hours, and then raised to saturation in 3-hours.

Smallmouth Bass (Micropterus dolomieu) - coolwater:
Smallmouth bass are at least as sensitive to low DO concentrations as northern pike. During in situ experiments (Ref. 5-105), hatching success of smallmouth embryos was 0 at 0.5 mg/L, only 69% at 1.8 mg/L and 87 to 91% at 3.5 to 7.9 mg/L and in controls. At a concentration

of 2.2 mg/L, survival of sac-larvae in 6-hour "in situ" tests conducted at natural spawning sites was only 53% at two days. Survival was 73 to 83% in controls and at 4.2 to 9.0 mg/L. However the life stage probably most sensitive to low DO, the larval, was not tested. Siefert at al (Ref. 5-37) found that no egg hatching occurred at a constant 1.2 mg/L (20°C) DO and that though hatching occurred at 2.5 mg/L (20°C), sac-larvae died by the fifth day of exposure. DO concentrations reduced to 50% saturation (4.4 mg/L) were not adequate for proper survival of smallmouth young at their optimal temperature (Ref. 5-37). Survival at 4.4 mg/L (20°C) was reduced nearly 20% when compared to controls; completion of hatch was accelerated; and average growth in length was reduced. Survival at a higher temperature (28°C) was reduced an additional 20% when compared to 20°C. Fry feeding ceases at DO levels less than 1 mg/L (Ref. 5-144).

Largemouth Bass (Micropterus salmoides) - warmwater:
The dissolved oxygen concentration at which a reduction in the resting metabolic rate of an organism first occurs is termed the "critical oxygen concentration". This point is believed to represent a marked reduction in energy use for growth and activity, a decrease in the supply of oxygen to tissues, and a partial shift to anaerobic energy production. Critical oxygen concentrations for the largemouth bass were (Ref. 5-145) 2.8 mg/L at 30°C; less than 2.6 mg/L at 25°C; and less than 2.3 mg/L at 20°C. Bouck and Ball (Ref. 5-48) also identified sublethal but stressing effects on largemouth bass from a diurnally fluctuating low DO pulse by exposing them to 3 mg/L DO for 8-hours per day for 9 days. This exposure led to effects such as dramatically increased blood clotting rate, modified serum proteins, interference with digestive processes and vomiting of undigested food, lethargy, loss of natural color, and increased ventilation rates. The DO level at which largemouth bass are not adversely affected is "well above" 3 mg/L (Ref. 5-48).

Total mortality has been reported for the largemouth bass under constant or declining DO levels from < 1 mg/L to 3.1 mg/L (Ref. 5-146 and 5-147). During experiments of constant exposure to low DO (Ref. 5-35), survival of largemouth bass was reduced at 35 and 20% saturation, but not significantly at 50 and 75% saturation. Dudley and Eipper (Ref. 5-148) also found that the survival of largemouth bass

embryos decreased markedly at 2.0, 2.1, and 2.8 mg/L at 15, 20 and 25°C (about 20-35% saturation), respectively. Beginning the second day after fertilization and continuing until the sixth day of life (Ref. 5-20), embryos and larvae of the largemouth bass become increasingly sensitive to oxygen deficiency, whether constant or varying. Thereafter they became more resistant, possibly due to the beginning of opercular movement on that day. For all days preceding and following the sixth (the most sensitive day), survival consistently increased as: exposure period to low DO became shorter (24 versus 6 versus 3-hours); oxygen concentration was higher (from 1 mg/L to 2.5 mg/L); and temperature was lower (25°C versus 20°C). All largemouth larvae died after only a 3-hour exposure to a DO concentration of 2.5 mg/L at 25°C (Ref. 5-20). Latent damage to the larvae's ability to open the mouth and feed after earlier exposure to low DO, was documented at all DO levels below 2.5 mg/L at 20°C. Even at 3 mg/L (20°C) and 4-5 mg/L (25°C) normally quiescent sac-larvae became very active, swimming vertically several centimeters. This behavior could result in drastically increased losses due to predation and displacement from nests. As for many species of non-salmonids, acute laboratory tests (24 to 96-hour duration) typically just do not accurately reflect the latent mortality that probably occurs.

Growth rates of the largemouth bass are dependent upon DO concentration at temperatures between 15 and 29°C. Between 20 and 29°C, growth impairment, and decreased food consumption has been demonstrated for all DO concentrations below saturation (Ref. 5-6). At 15°C, dependence of growth rate on DO levels was apparent only at about 3.5 mg/L and below. Thus, there appears to be a critical temperature between 15 and 20°C, above which growth rates of largemouth bass are depressed by even moderate reductions in DO level below saturation.

The growth and food consumption rates of juvenile largemouth bass subjected to widely fluctuating DO concentrations (Ref. 5-6) were markedly less than their estimated growth at constant concentrations equal to the means (arithmetic and geometric) of the fluctuating concentrations. Mean lower limit was about 2 mg/L and the mean upper limits in this study were about 6, 8 or 17 mg/L, depending upon treatment. The fish were exposed daily to high and low concentra-

tions, usually for equal periods following periods of gradual transition. Low concentrations occurred at night and early in the morning. The growth of fish subjected to these diurnally fluctuating conditions often proved equivalent to that which would have occurred at constant levels only a little above the lower limit of the wide fluctuations. Exposure to cycling oxygen levels with daily minima of about 2 mg/L and daily maxima of 4 to 17 mg/L reduced growth of juveniles held at 26°C (Ref. 5-44). Under any fluctuating regime the growth occurring was almost always less than that expected should the fish have been held at a constant concentration equal to the mean concentration.

Carlson and Siefert (Ref. 5-35) also reported decreases in growth of larvae with any reduction of DO below saturation. Concentrations from 1.7 to 6.3 mg/L reduced growth of early stages 10 to 20 percent. Even at concentrations as high as 4.5 mg/L hatching was premature and feeding was delayed, both factors which could lead to increased mortality of young. Growth of juvenile largemouth is reduced at 5.9 mg/L DO and below (Ref. 5-44). Concentrations of 5.1 and 5.4 mg/L DO produced reductions in growth rate of 20 and 14% respectively, whereas 5.8 and 5.9 mg/L had no effect on growth. A limited study conducted in artificial ponds (Ref. 5-149) indicated that a 2.5 mg/L reduction in DO concentration below saturation at 26°C resulted in a 17% reduction in the mean growth rate of juvenile bass. Though the data are limited, good agreement between this "mesocosm" study and a laboratory study (Ref. 5-150) on the degree of correlation between growth rate reduction and reduced DO levels, was observed. Overall, the growth rate response to low DO for largemouth bass appears to be intermediate between the more sensitive salmonids and northern pike and the less sensitive yellow perch (Ref. 5-2).

Juvenile largemouth show distinct avoidance of 1.5 mg/L and some avoidance of DO levels at or below 4.6 mg/L (Ref. 5-19 and 5-6). Final maximum sustained swimming speeds are reduced (Ref. 5-23 and Ref. 5-6) below 5 to 6 mg/L (60 to 72% saturation) DO. Swimming ability by the largemouth bass in reduced oxygen may also be affected by temperature and season. Katz et al. (Ref. 5-22) reported that 6-cm largemouth bass could resist water current of 25 cm/s at 25°C in September at oxygen levels as low as 2.0 mg/L. However at 15-17°C in

December they were unable to do so even at 5.0 mg/L. As for salmonids swimming performance of largemouth bass appears to be more affected by low DO at lower temperatures.

The distribution of largemouth bass within some reservoirs appears to be seasonally limited by DO levels. Within two southwestern reservoirs (Ref. 5-27), the factor most strongly associated with the distribution of largemouth bass and their prey was their limitation to areas with DO levels greater than 2 mg/L, rather than euphotic zone or temperature.

Crappie (Pomoxis spp.) - warmwater:
Both the white (Pomoxis annularis) and the black (P. nigrmaculatus) crappies are discussed here. Lethal DO limits and conditions for the crappies have not been well defined. Acute mortality for the white crappie at 0.4 mg/L was reported as 100% (Ref. 5-139), if fish were denied access to the surface and 50% if allowed access to the surface. Fish held in the laboratory with daily fluctuations in DO conditions of 1.8 to 4.1 mg/L exhibited aberrant behavior of breaking the water surface with their mouths, increased gill ventilation, erratic swimming behavior, and loss of color. These changes were observed cyclically and coincided with the lowest portion of the diel fluctuations in DO concentration. However, mortalities did not occur. In acute field tests of 24 or 48-hour duration (Ref. 5-146), for the black crappie, 100% mortalities have been reported at 1.4 mg/L DO in winter at 4°C, and 4.3 mg/L DO in summer at 26°C. Fish were held in cages submerged in a lake at relatively constant DO levels. Sigler and Miller (Ref. 5-151) reported that DO levels below 1.4 mg/L also often cause mortality in black crappie populations.

White crappie were found in reservoirs at DO concentrations as low as 3.3 mg/L (Ref. 5-152), but were rarely found at 2.0 mg/L (Ref. 5-153). Whether these DO levels constitute less than optimal DO conditions for growth, long-term survival, or production impairment of crappie in the field is not known.

Exposed in two sets of laboratory tests to constant DO concentrations of 2.5, 3.5, 4.0, 5.0, 5.5, 6.5 and 7.0 mg/L and ambient (Ref. 5-18 and Ref. 5-46), mature black crappie spawned at all concentrations.

No discernable effects of reduced oxygen at the levels tested were observed on spawning success, numbers of embryos produced, viability, hatching success or larval survival through the swim-up stage. However, timing of spawning appeared affected by DO concentration. Fish held at 2.5 mg/L exhibited territorial behavior, and started and finished spawning sooner at lower temperatures than fish held at higher DO levels. Fish held at saturation were among the last to spawn and this occurred at the highest spawning temperatures. Inducement of early spawning could affect the survival of offspring in the natural environment, but the production impairment or ecological significance of early spawning is at present unknown.

Fish exposed to mean diel DO fluctuations from 0.8 to 1.9 mg/L above and below concentrations of 2.5, 4.0, 5.5, and 7.0 mg/L successfully spawned at all concentrations except the lowest fluctuating treatment of 1.8 to 4.1 mg/L, where no spawning occurred (Ref. 5-46). These studies indicate that concentrations of 2.5 mg/L DO or above are adequate for overwintering and spawning of black crappie, and that diel fluctuations down to 1.8 mg/L causes hypoxic stress, inhibiting reproduction.

Yellow Perch (Perca flavescens) - coolwater:
Young yellow perch appear to be more tolerant of lower DO concentrations and more adaptable to moderate and gradual diurnal DO fluctuations at low DO concentrations than many other fishes. Survival of juvenile yellow perch in 67-day laboratory tests was not affected by either constant or diurnally fluctuating DO levels between means of 1.4 to 8.5 mg/L (Ref. 5-45). In the constant DO tests, consumption of food was somewhat reduced at 3.5 mg/L, and notably so at 2.0 mg/L and below. Significantly reduced growth occurred only with fish reared near 2.0 mg/L. Reductions in weight gain were 2, 4, and 30% at 4.9, 3.5, and 2.1 mg/L, respectively. Carlson et al. concluded that mean diurnal fluctuations of 3.8 to 1.4 mg/L DO did not affect growth, even though the percentage weight gains from initial weights were significantly lower for fluctuating DO's when compared to constant DO levels with similar means (79 to 93% weight gain versus 155 to 216%, respectively). Instead, they attributed the differences to possible other factors such as food quality, greater disturbance by experimenters of fish in fluctuating DO tests, genetic differenc-

es, differences in initial starting weights, or environmental history.

Short-term (less than 5 days duration) laboratory and field studies on the winter DO requirements of yellow perch have determined that levels from 0.2 to 1.5 mg/L DO are lethal to adults (Ref. 5-146, 5-96, and 5-97). However, 3.5 mg/L DO was lethal (Ref. 5-146) at a summer temperature of 26°C.

Walleye (Stizostedian vitreum) - coolwater:
Although most investigations have related the spatial distribution of walleye in terms of food availability and depth of light penetration, the distribution-limiting effects within reservoirs of low DO on walleye and their congener, the sauger, has long been recognized (Ref. 5-29). Adult walleye can tolerate a DO concentration of 2 mg/L for short periods of time (Ref. 5-28), but the greatest abundance of walleye in reservoirs occurs where DO levels are greater than 3 to 5 mg/L. Walleye lose their negatively phototactic (light avoiding) behavior at 2 to 4 mg/L DO and concentrations below 1 mg/L are lethal to adults (Ref. 5-28).

Adult walleye in reservoirs appear to undergo a thermal-DO "squeeze" somewhat similar to that experienced by the striped bass. In a reservoir in Tennessee, Dendy (Ref. 5-29) documented the movement of walleye out of areas where DO levels had dropped to 0.0 to 1.5 mg/L, into the upper portion of the reservoir where DO concentrations were at least 3 mg/L. As the seasonal depletion of DO advanced, both walleye and sauger were forced into much warmer water temperatures (70 to 80°F, and 60 to 70°F) than those customarily occupied by adult walleye and lethal for early life history stages (Ref. 5-9). Dissolved oxygen levels above 3 mg/L did not appear to affect walleye distribution within reservoirs. In comparison, sauger appeared slightly more tolerant of low DO, the majority remaining in areas with 1.6 to 3.0 mg/L, but were forced to either move downstream or up above the low DO water when levels fell to 0.0 to 1.5 mg/L. Avoidance of these low level DO indicates stressful conditions. Scott (Ref. 5-154) and Ager (Ref. 5-155) also documented the summer confinement of walleye in Center Hill reservoir of Tennessee to shallower areas of higher DO just above the thermocline, where, although

temperatures were less than optimal, the coolest water with sufficient DO was found.

DO levels greater than or equal to 5 mg/L are considered necessary for high survival and growth of embryos (Ref. 5-156). As indicated by a lack of carotenoid pigments, a poorly developed temporary embryonic respiratory system, and characteristics of adult spawning sites, embryos and larvae of the walleye require well-oxygenated water for survival and development (Ref. 5-157 and 5-158). Siefert and Spoor (Ref. 5-9) conducted continuous-level laboratory tests on walleye eggs and larvae of 12.5, 20, 25, 35, 50 and 100% DO saturation at 17°C (1.2, 1.9, 2.4, 3.4, 4.8, and 9.6 mg/L DO, respectively); and 25, 50 and 100% saturation at 20°C (2.2, 4.5, and 8.9 mg/L DO, respectively). Survival at 50% saturation (4.8 mg/L at 17°C) was comparable to that in 100% saturation controls. Survival was drastically reduced at 35% saturation (3.4 mg/L at 17°C) and all larvae at lower concentrations died before initiation of feeding. At 12.5% saturation (1.2 mg/L at 17°C) all eggs died before hatching. At 35% saturation and above most mortality occurred to larvae, whereas at saturations below 35% most mortality was that of eggs. At 20 to 25% saturation larvae were noticeably weak swimmers.

Dissolved oxygen concentrations of 3.4 mg/L or lower result in delayed hatching, significant reductions in size at hatching and poor swimming ability (Ref. 5-159, 5-160, 5-156 and 5-8). Optimal DO conditions for fry are concentrations above 5 mg/L (Ref. 5-8). Moyle and Clothier (Ref. 5-161) also observed poor survival of stocked fry below 5 mg/L.

Section 6

TECHNIQUES FOR IMPROVING DISSOLVED OXYGEN LEVELS

As indicated in Figure 6-1, alternatives for dissolved oxygen supplementation of hydropower discharges can be divided into the following six categories:

Tailrace Techniques
Powerhouse Techniques
Reservoir Techniques
Operational Techniques
Combinations of Techniques
Techniques Under Development

Tailrace Techniques include methods downstream of the powerhouse. This manual will discuss weirs, surface aerators, and diffuser systems. Powerhouse Techniques include methods both within and immediately upstream of the powerhouse, such as turbine venting, draft tube aeration, and gas injection in the forebay. Reservoir Techniques include reservoir destratification and hypolimnion aeration.

Operational Techniques are methods of controlling DO levels without the addition of specialized aeration equipment. These techniques include bypass systems such as spillway release, the use of Howell-Bunger valves, and operational constraints such as operating the turbines only when the diurnal DO fluctuations of the reservoir are such that water quality standards can be met.

Combinations of Techniques involve at least two systems from each of the four preceding categories. The more promising combinations include draft tube aeration enhanced with pure oxygen injection, epilimnetic surface pumps combined with oxygen injection, and draft tube aeration with a downstream weir.

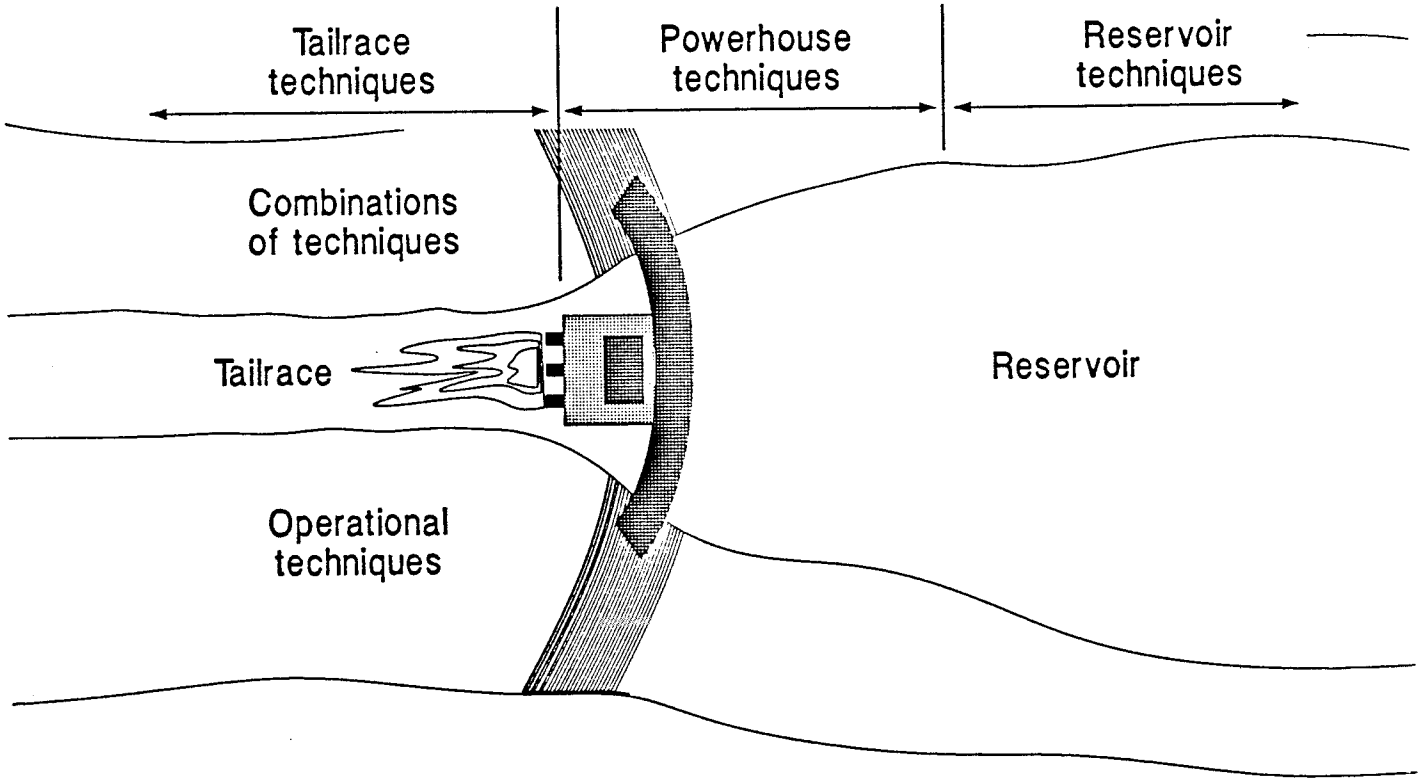


Figure 6-1. Aeration Classification Systems

Techniques Under Development are approaches that have not been widely tested, yet potentially hold promise. These approaches mainly involve sidestream injection technology, and, as such, are particularly applicable to low head, run-of-river facilities.

The above categories are discussed in detail in sections 6.1 through 6.5.

6.1 TAILRACE AERATION TECHNIQUES

Weirs

Physical Aspects. Weirs have the potential to produce abrupt changes in stream elevation and induced turbulence due to significant increases in dissolved oxygen concentrations. In Minnesota, increases in dissolved oxygen at spillways ranged from 1.5 mg/L to 5.0 mg/L (Ref. 6-1). In Illinois, Butts and Evans (Ref. 6-2) gathered field data which indicated as much as 2.5 mg/L could be added by a small channel dam, and confirmed considerable aeration could be achieved at weirs with heights in the 1-foot to 5-foot range. More recently, an aeration weir installed on the Guadelupe River in Texas was able to achieve a DO increase of more than 5 mg/L (initial DO: 0.3 mg/L; final DO: 5.3 mg/L) with a head loss of approximately 3-feet. These cases all indicate that weirs are capable of appreciable increases in dissolved oxygen.

A weir constructed for the sole purpose of aeration, as illustrated in Figure 6-2, would typically result in a headloss of 2- to 5-feet, be configured to cross the channel in a zigzag fashion to increase crest-length, be of the sharp-crested (vertical drop) type, have a plunge pool of 4- to 10-feet in depth, and incorporate a means to allow the tailrace to operate at normal levels when reservoir releases meet dissolved oxygen standards without additional aeration.

Working Principles. The aeration that occurs at a weir is identical to that associated with waterfalls and cascades. Water is exposed to the atmosphere on both sides of the nappe. The nappe entrains air as it impinges on the tailwater and the bubbles are submerged for a certain residence time, allowing mass transfer of oxygen from the bubbles to the water. Existing equations, however, for sizing weirs

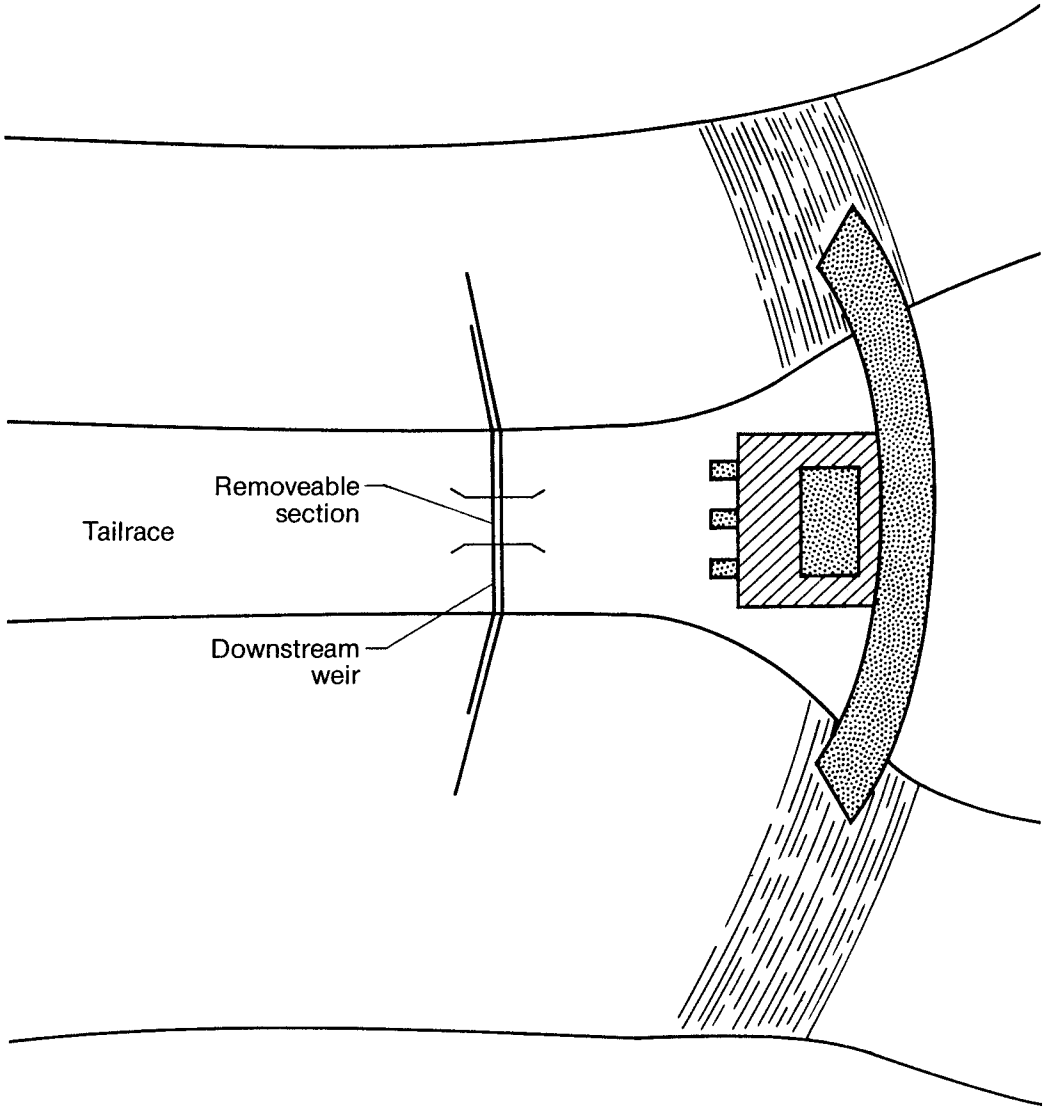


Figure 6-2. Typical Installation of Aeration Weir.

are somewhat contradictory, and methods for predicting the aeration capacity of a structure need improvement. The important variables identified with the process of weir aeration are: 1) elevation change over the weir from headwater to tailwater, 2) flow rate over the weir per unit length, 3) plunge pool depth, 4) water quality, 5) weir geometry, 6) temperature, 7) DO saturation concentration, and, 8) upstream DO concentration.

It is interesting to note that in early studies, flow per unit length of weir was disregarded as an important variable, and, as such, has added a degree of difficulty in designing today's structures. Gameson (Ref. 6-3) was one of the first to study the aeration effects of weirs, and found that increasing flows by a factor of 3 to 4 had little effect on aeration. More recent efforts by Markofsky, et al. (Ref. 6-4), Mastropietro (Ref. 6-5), Avery and Novaky (Ref. 6-10), and Nakasone (Ref. 6-6) consider the effect of flow volume, although from different approaches. Their work should be closely studied and evaluated when designing aeration weirs.

Even though Gameson disregards flow-volume per unit length and plunge pool depth, it has served well as a starting point for many researchers. The following weir-aeration equation was originally provided by Gameson (Ref. 6-3) and refined by the British (Ref. 6-7):

$$r = 1 + 0.38abh(1 - 0.11h)(1 + 0.046T) \qquad (6\text{-}1)$$

where:

r = deficit ratio
a = water quality factor
b = structure aeration coefficient
h = height, (headwater - tailwater), meters
T = water temperature, °C

The parameters influencing aeration over weirs are discussed in more detail below. Equation (6-1), as presented, is considered reasonably accurate for falls up to 3-meters.

Deficit Ratio:

Oxygenation effectiveness is measured in terms of a dimensionless "deficit ratio", r, defined as:

$$r = \frac{C_s - C_u}{C_s - C_d} \qquad (6\text{-}2)$$

where:

C_s = oxygen saturation concentration (mg/L)
C_u = oxygen concentration in the headwater (upstream) (mg/L)
C_d = oxygen concentration in the tailwater (downstream) (mg/L)

Refer to Appendix G for a discussion and tabulation of oxygen saturation concentrations vs. temperature and atmospheric pressure. If the DO level in the water increases by passing over the weir, the DO deficit is decreased and the deficit ratio will be greater than 1.

Example:

Water, at 15°C passes over a weir. The upstream DO level is 6.4 mg/L; downstream it is 8.6 mg/L. Appendix G lists the DO saturation of water at 15°C as 10.03 mg/L. Therefore, the deficit ratio under these conditions is:

$$r = \frac{10.03 - 6.4}{10.03 - 8.6}$$

$$r = 2.54$$

The importance of the deficit ratio is that researchers have found it to be relatively independent of the upstream DO content. Thus, if "r" is measured at an existing structure, DO uptake can be predicted for other upstream DO conditions using Equation (6-2) (Ref. 6-7).

Water Quality Factor:

According to Notes On Water Pollution (Ref. 6-7), surfactants, sewage, or sewage effluent tends to depress oxygen exchange.[1] This effect is taken into account by the water quality factor, "a". Currently accepted values for the water quality factor are presented in Table 6-1 (Ref. 6-2).

Table 6-1

WATER QUALITY COEFFICIENT, a

Condition of the water	Water Quality Coefficient, a
Grossly polluted	0.65
Moderately polluted	1.0
Slightly polluted	1.6
Clean	1.8

The wide interpretation of moderately polluted, slightly polluted, and clean water is subjective, and directly affects the overall deficit. For typical hydroelectric applications, a value between 1.2 and 1.4 should suffice.

Structure Aeration Coefficient:

The structure aeration coefficient, "b", is used to account for various weir geometries. Although many weir geometries exist (Ref. 6-2), the best configuration for hydroelectric aeration applications will be the vertical weir (b = 1.0) or the stepped weir (b = 1.3). The overall aeration ability of stepped weirs depends on several factors, including number of steps, step height, and slope. Even though increased aeration efficiency of stepped weirs has been noted by many researchers (Ref. 6-3, 6-7, 6-8, 6-9), Nakasone (Ref. 6-6) suggests that the increase is not appreciable until the overall fall height is greater than approximately 4-feet. Because economics will dictate weir design, for hydroelectric applications, single step weirs are probably favored.

[1]According to Avery and Novak (Ref. 6-10), however, $NaNO_3$ increases aeration.

Water Temperature:
According to the British (Ref. 6-7), aeration increases linearly as temperature increases, the rise per degree-C being 4.6% of the aeration value at 0°C. This relationship is incorporated into Equation (6-1).

Depth of Receiving Water:
It is known that for a given fall height, the degree of aeration depends on the depth of the basin into which the water falls. From the works of Pöpel (Ref. 6-92) and Albrecht (Ref. 6-93), Nakasone suggests that plunge pool depth be equal to 2/3 x fall height, h.

Flow Rate:
The flow per unit length over a weir is a parameter often missing from aeration equations, and widely varying results have been encountered in the research. From Nakasone (Ref. 6-6), Khudenko (Ref. 6-94) suggests that optimum aeration at broad-crested weirs occurs between a flow of 0.43-CFS/ft and 0.59-CFS/ft; Albrecht (Ref. 6-93) mentioned an optimum flow rate of 0.60-CFS/ft. Nakasone suggests 0.70-CFS/ft.

Because hydro flows are usually large, it may be advantageous for owners to increase the flow per unit crest length, sacrificing "optimum aeration", but saving on construction costs. Markofsky, et. al (Ref. 6-4) applied a broad boundary condition of 2.15-CFS/ft to 5.37-CFS/ft. In recent TVA investigations, a flow of 1- to 2-CFS/ft has been used as a safety precaution to prevent unsafe downstream "rollers" from developing.

Limitations, Constraints, and Trade-offs. The most obvious trade-off a weir imposes is the loss of head associated with its installation, and the resulting decrease in generated power. If the tailrace conditions are favorable, it may be possible to locate the weir far enough downstream to have no headloss at the hydroplant. However, a weir not in the near vicinity of the powerplant increases the risk of vandalism, and presents a greater safety problem.

Major Obstacles To Installation. Topography of the existing tailwater will determine the degree of difficulty when installing a weir.

If the powerhouse is simultaneously undergoing construction, the tailrace may already be de-watered, and weir construction is relatively easy. Some weirs, such as rockfill timber cribs and gabions, are installed in shallow water, and may not necessarily require de-watering. However, if the tailrace must be de-watered and equipment brought in to prepare the foundation, appreciable added cost will be incurred.

If a facility incorporates a deep tailwater, economics would dictate that the weir be located further downstream, at a shallower location.

Environmental Effects. Environmentally, weirs can present appealing visual and audio impact. However, if they are located an appreciable distance downstream of the hydroelectric facility, they should be environmentally appraised as any other river diversion or obstruction device (i.e., obstruction to fish migration, promotion of algae and weed growth in pool, aid to meeting minimum flow requirements).

Life Expectancy. Because weirs aerate using no moving parts, their life expectancy is generally very long, depending on the materials of construction. A concrete structure should be designed to last 40- to 50-years with minimal maintenance. Rockfill weirs last about 20-years.

Safety. Weirs applied for aeration purposes are relatively low in height 1- to 5-feet), and may present a hazard if suddenly breached. Weirs are attractive structures to the public, and rollers downstream from them are notorious for being hazardous. Safety may control the length of a weir. Facilities that have both high flows (greater than 3,000 CFS, approximately) and narrow channels may encounter dangerous hydraulic conditions downstream of a weir. TVA has found that flows much greater than 1 CFS per foot of crest length can result in "rollers" downstream. Safety may control the length of a weir more than aeration. If the structure is not located near the powerhouse, additional safety precautions may also be necessary to protect boaters.

Modes of Failure. Because the aeration that occurs at weirs is a passive process, modes of failure are few. The only realistic

failure that might occur would be the collapse of a section of weir, such as the removable portion. However, because weir design is very basic, modes of failure are relatively obvious and can be avoided. Still, if a failure should occur, repairs are generally simple.

If inflatable dams are used for the removeable section, compressor failure must be considered. Usually, an extra compressor to serve as a backup is supplied. Small punctures, such as bullet holes, generally have little effect, and can be repaired when the turbine is not operating.

Level of Confidence. For reasons discussed above, in spite of the large number of investigations performed to date, the risk of a weir not performing exactly as expected is somewhat high. The correlation of laboratory data to field installations has been poor. If a weir appears to be a viable alternative when compared to other aeration approaches at a particular site, a preliminary field test of a small section of weir would be a prudent investment.

Sizing.

Working Example #1:

Assumed conditions:

Water temperature: 15°C
Pollution conditions: Moderately/Slightly Polluted (a =1.3)
Weir Configuration: Standard, Vertical, Single Step (b = 1)
Upstream DO concentration: 2.0 mg/L
DO discharge requirement: 5.5 mg/L
Local Barometric Pressure: 760 mm
Weir Height: To be determined.

Under the above conditions, dissolved oxygen saturation concentration, C_s, would be 10.0 mg/L. Using Equation (6-2):

$$r = \frac{(10.0 - 2.0)}{(10.0 - 5.5)} = 1.78$$

Using Equation (6-1) and solving for h:

$$1.78 = 1 + 0.38(1.3)(1)(h)(1-0.11*h)(1 + 0.046*15)$$

$$h = 1.06 \text{ meters } (3.48 \text{ feet})$$

If the upstream DO level were to change, "r" would remain constant, and the new downstream DO level could be calculated using Equation (6-2). Assuming the upstream DO decreases to 1.0 mg/L:

$$1.78 = \frac{(10.0 - 1.0)}{(10.0 - C_d)}$$

Solving for C_d:

$$C_d = 4.94 \text{ mg/L}$$

Thus, a decrease of 1 mg/L upstream lowered the DO level below the weir by 0.56 mg/L.

Working Example #2:
To investigate the theoretical performance of two single-step weirs, each with a fall height of 0.4 meters (16-inches), acting in series, the conditions of the above example are used (T = 15°C, C_u = 2.0 mg/L, a = 1.3). Equation (6-1) results in r = 1.33 for each weir. From Equation (6-2), C_d of the first weir is 4.0 mg/L. The C_d of the first weir becomes C_u of the second weir. Again using Equation (6-2), the final C_d is equal to 5.5 mg/L. Thus, under these conditions, a series of two single-step weirs with fall heights of 16-inches each provide the same aeration as a single weir with a fall height of 42-inches. An economic comparison of additional construction costs versus the smaller headloss of the stepped weirs would be necessary to determine which approach is most cost-effective.

Cost of Working Example #1:
As illustrated in Figure 6-3, the construction height of a weir is composed of several measurements, all of which can be referenced to the existing tailwater elevation. It is assumed that the downstream tailwater elevation will essentially be the same after the weir is in place. The construction height of the weir (P), is the tailwater depth (d), plus the fall height (h), minus the height of the water surface above the crest of the weir (H). The fall height, h, was determined to be 3.48 feet. The USBR (Ref. 6-11) provides the following equation that can be used to calculate H:

$$Q = 3.33(L - 0.2H)H^{3/2} \qquad \text{(Equation 6-3)}$$

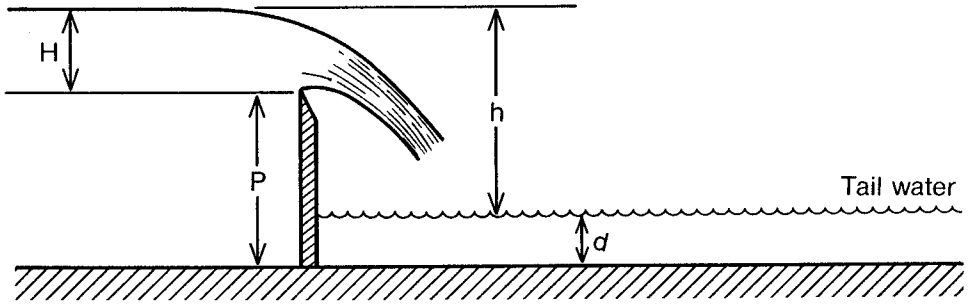


Figure 6-3. Basic weir design parameters.

where:

Q = flow in CFS
L = crest length (feet)
H = height of water surface above crest (feet)

Thus, if the discharge from the facility is 600 CFS and the flow over the weir is assumed as 1 CFS per foot, the length (L) would be 600-feet. Using Equation (6-3), H would be 0.45-feet. If the weir is located at a point downstream of the dam where the tailwater depth (d) is 3.0-feet, the actual construction height of the weir would be 3.0 + 3.48 - 0.45 = 6.03-feet.

Construction details of a weir will be very site-specific. However, assuming a cross-section for the structure as shown in Figure 6-4 to calculate concrete volume, 133 cubic yards would be required for the vertical portion of the weir, and 111 cubic yards for the foundation slab. Means Building Construction Cost Data 1989 (Ref. 6-12) indicates cast-in-place ground slabs, 12-inches thick, average $3.33/square foot, and that 12-inch thick grade walls average $360/cubic yard. This results in the basic weir costing approximately $58,000[2]. An additional $10,000 will be allowed for abutments and any special concrete work. Flap gates similar to those described in the Case Study, below, could be provided to allow the tailwater to be operated at a normal elevation. Assuming each gate opening to be 8-feet long and 3-feet high, 8 gates would be required, costing approximately $1,000 each. To allow the weir to be drained, two 18-inch slide gates would be installed, also costing $1,000 each.

Dewatering the tailrace and excavation can add considerable cost to a project. If the construction is done simultaneous to other work requiring the tailrace to be dewatered, appreciable savings can be realized. Assuming the worst, approximately 4,300 cubic yards of fill would be required for a temporary dam, allowing the powerplant to operate during construction. The cost of placing, compacting, and removing the temporary dam after weir completion is approximately

[2]This example only considers a weir in a straight configuration. Should the weir length be such as to require a "W" configuration or something similar, additional costs will be incurred.

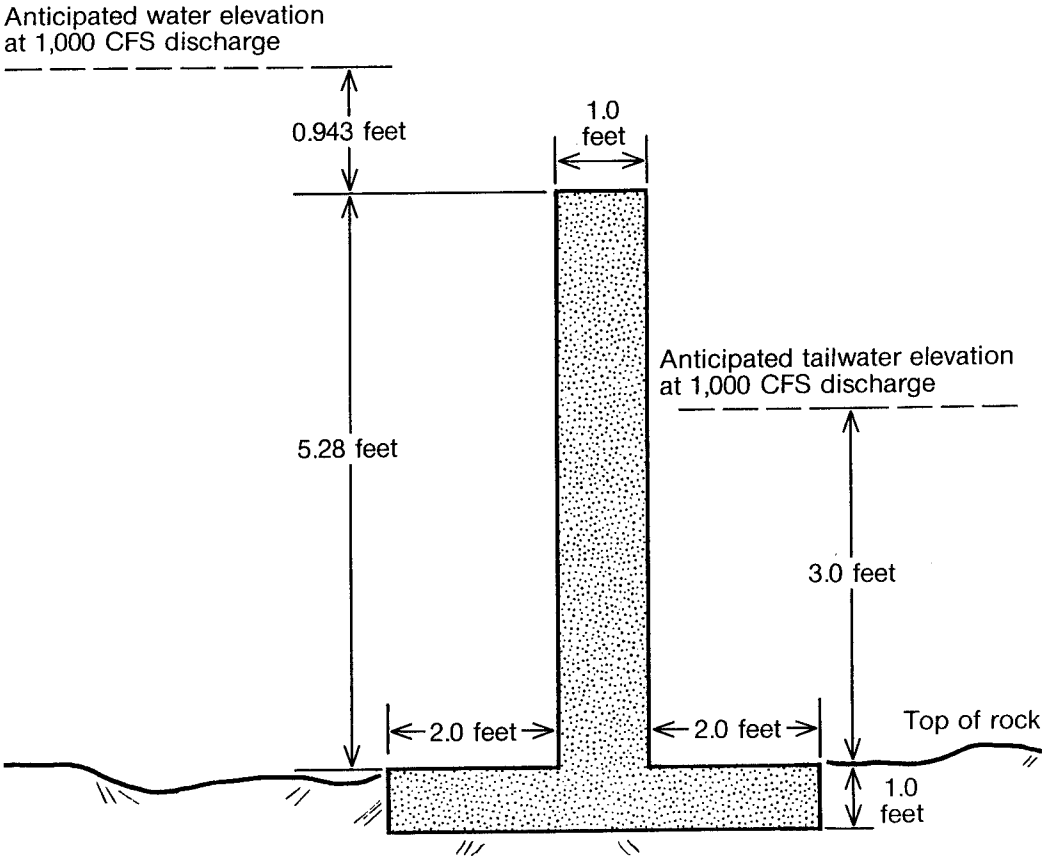


Figure 6-4. Typical Cross-Section Through Hypothetical Weir.

$120,000. Once dewatered, approximately 111 cubic yards of rock will require excavation at $100/yard, totaling $11,100.

Miscellaneous costs could include rock anchors, abutment drainage, gangways, and handrails. For this example, these costs will be estimated at $20,000.

Summarizing, the installed cost of the weir are estimated to be:

Weir construction (333-feet):	$58,000
Weir abutments/specialties:	10,000
Flap gates (13 at $1,000 ea.):	8,000
Slide valves (2 at $1,000 ea.):	2,000
Temporary dam:	120,000
Rock excavation:	11,100
Miscellaneous:	20,000
Installation cost:	$229,100
Engineering (10% of cost):	22,910
Total, installed cost:	$252,010

Annual costs would include insurance, a small amount for labor to raise and lower the flap gates, and occasionally cleaning the structure. When the weir is in operation, the turbine suffers a headloss, causing a reduction in power revenues.

For this example, it will be assumed that the turbine operates at 90% efficiency. A headloss of 3.48-feet (at 600 CFS) would result in a loss in generation of 159-kilowatts. If the weir is operational 5-months of the year, and the facility generates 6-hours per day, the total for lost power revenues (at $0.06/kwh) is $8,586.

If the structure is assumed to have a 50-year life expectancy, the insurance costs can be estimated as 1/50th of the installed cost (less engineering fees).

Summary of annual costs:

Maintenance/labor:	$2,000
Insurance (2% of installation):	4,582
Lost power revenues:	8,586
Total annual costs:	$15,168

To allow comparisons with other examples in this manual, the costs will be extrapolated over a 30-year period, typical of many licenses issued today. The Present Worth of the above annual cost over a thirty year period at 12% is $122,178.

Total Present Worth:

Initial installation:	$252,010
Annual costs, Present Worth:	122,178
Total Present Worth:	$374,188

(Equivalent to $46,454 annually for 30-years.)

Case Study. Only one installation of a weir for the specific purpose of aerating hydroelectric discharges is known. Located immediately downstream of the Canyon Dam on the Guadelupe River in Texas, the installation is illustrated in Figure 6-5. The powerhouse contains two 3-MW generating units with a maximum total hydraulic capacity of 600 CFS. A DO deficit exists 6-months of the year, and averages 4 mg/L, with a maximum deficit of 6 mg/L.

Seven different aeration systems were evaluated to address the deficit. Included were large-bubble compressed air diffusers, oxygen injection, spray aerators, and instream weirs. The owner selected a combination of turbine venting and a downstream weir.

The "W"-shaped weir is 385-feet long, 3.5-feet high, fits into an area 40-feet wide by 113-feet long, and was designed to produce an average fall of 3-feet over the normal flow range of the powerhouse (90 CFS to 300 CFS). The design is largely based upon the findings of Avery and Novak (Ref. 6-10). Operation of the weir results in a reduction in head of 3.5 feet, or 2.5% of the available head. The

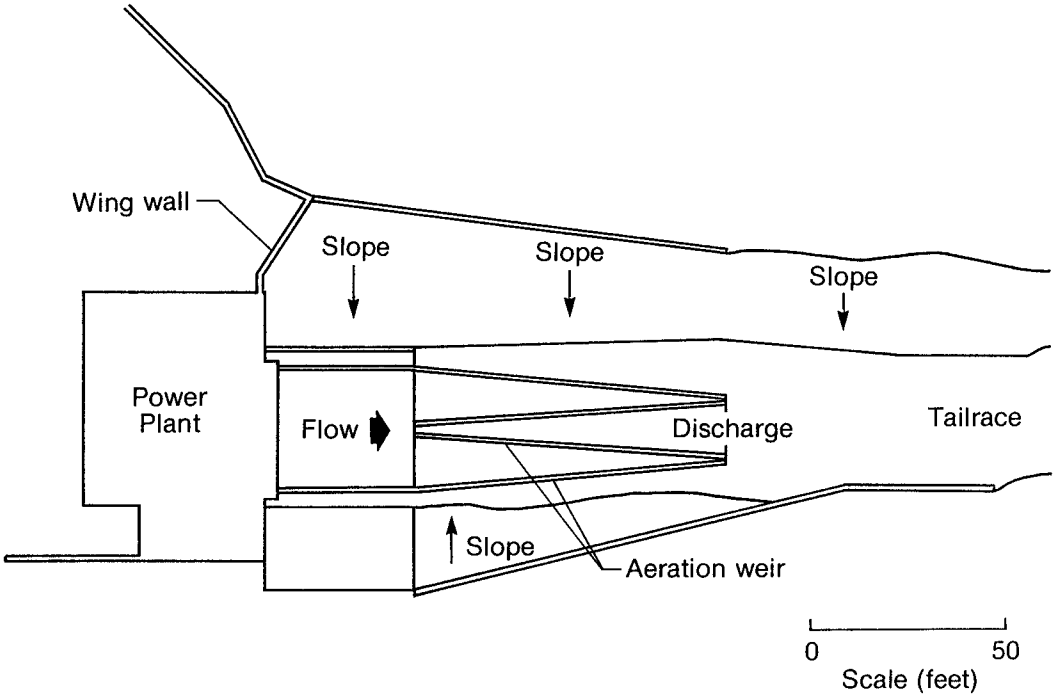


Figure 6-5. Aeration Weir at Canyon Dam, Texas

weir can be taken out of service by manually opening twelve flap gates, each with an opening of 7.33-feet by 2.67-feet. The cost of the weir was estimated to be approximately $60,000. However, because the weir was constructed simultaneous to other construction at the site, the tailrace was already dewatered and material prices were reduced. Cost estimates at other sites would be somewhat higher.

The weir was first operated on May 30, 1989, when the powerhouse discharge DO level dropped below 6.0 mg/L. Unfortunately, dry conditions in the upper portion of the watershed have not allowed the weir to be tested at flows in the 300 to 600 CFS range. Table 6-2, however, presents a sampling of the data gathered thus far.

Table 6-2

AERATION PERFORMANCE OF WEIR AT CANYON DAM, TEXAS

Date	Flow (CFS)	Penstock DO (mg/L)	DO Upstream of Weir	DO Downstream of Weir
5/31/89	110	5.8	5.8	8.6
6/06/89	110	5.4	5.4	8.2
6/19/89	224	5.3	5.3	8.1
7/26/89	110	3.0	3.0	6.8
10/12/89	120	0.4	0.4	5.4
11/03/89	Turbine venting began			
11/03/89	118	0.3	4.8	7.4
11/03/89	187	0.3	2.1	6.4
11/17/89	171	0.8	3.1	6.4

It is interesting to note the small effect varying the flow has on the aeration action of the weir, but the major effect it has on the performance of the turbine aeration system.

Tailrace Gas Injection Techniques

The most obvious location to treat hydroelectric plant discharges is in the tailrace. Because the tailrace is in close proximity to the powerhouse, an aeration system can be operated and observed by powerhouse personnel, and yet the equipment is separate from the generation plant. The shallower depths and generally easier accessi-

bility of the tailrace are also advantageous to system installation. However, the shallow depths are also a major disadvantage in aeration efficiency and oxygen absorption, and will result a larger overall system, and higher maintenance. The disadvantages are generally great enough to cause the aeration system to be located either in the upstream reservoir or the powerhouse.

The two most common tailrace aeration systems considered are submerged diffusers supplied with air via compressors, and surface aerators. A detailed discussion of each of these approaches is presented on the following pages. It should be pointed out that the surface aerators are not the typical floatation-type familiar to most hydro owners. Floating aerators are not competitive with more state-of-the-art aeration systems. A newer, aspirating-type surface aerator, however, should be considered.

Tailrace Gas Injection / Submerged Diffusers

Physical Aspects. As illustrated in Figure 6-6, an air-supplied diffuser system would consist of an array of diffusers anchored in the tailrace, supplied by compressed air from the stream bank. If the aeration demand were seasonal and of short duration, it is conceivable that the diffuser array could be removed during extended periods of non-usage, thereby allowing maintenance to be performed and preventing damage from high flows. The diffuser array could also be staged, and supplied by individual compressors that could be stepped online as the DO deficit and flow volume required.

Diffusers are generally classified in two categories: porous and nonporous (Ref. 6-13). Porous diffusers are made from ceramic, plastic, or flexible materials, and are available as plates, domes, discs, or tubes. Nonporous diffusers are available in an even greater variety of sizes and types, but are not considered appropriate for the aeration of hydropower discharges due to their inherent larger bubble sizes and reduced oxygen transfer efficiencies.

Because of the field experiences gained by other users, this study will only consider the application of flexible membrane type porous diffusers. Other types of porous diffusers used in shallow-depth aeration applications, have resulted in poor transfer efficiency (4%

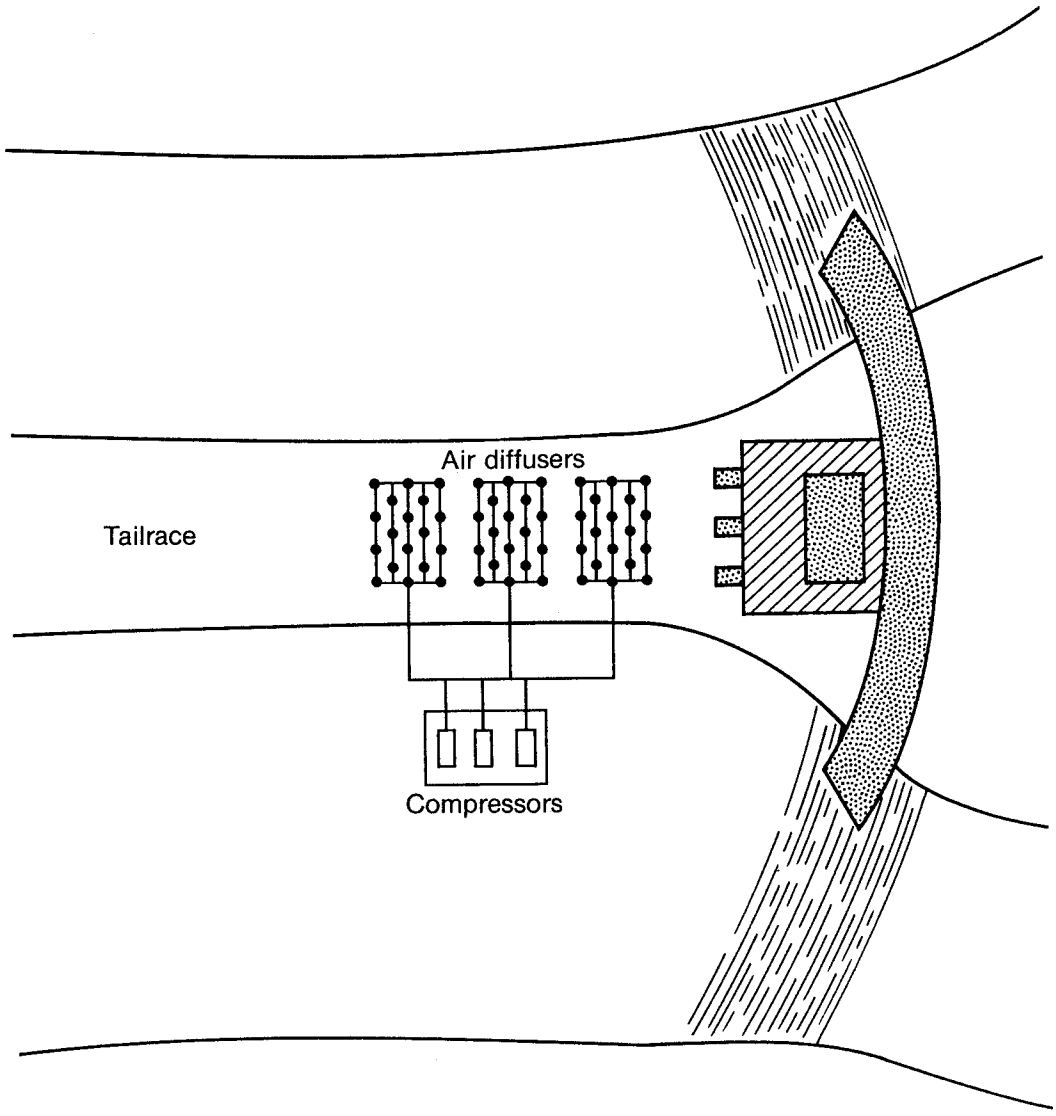


Figure 6-6. Tailrace/Submerged Air Diffuser System.

to 12%, typically) and were subject to breakage and fouling. Plastic, flexible membrane disk-types are relatively new, and overcome many of the problems encountered in past applications. Due to their inherent flexing action, the membrane nearly eliminates the fouling associated with other types of porous diffusers. The plastic diffuser (Figure 6-7) is impervious to normal chemical degradation, may be installed in the header without the use of tools, and is considerably less expensive to purchase. Transfer efficiencies in the 20% to 35% range are reported.

Working Principles. Diffuser arrays are regularly used to aerate wastewater treatment flows, and the application is nearly identical to that of tailrace aeration systems, particularly with respect to the depths involved. Compressed air is introduced via diffusers, and a portion is absorbed while in contact with the water. The air pressure required is determined by the depth of the diffuser and the pressure losses in the system. The amount of oxygen absorbed depends upon the airflow rate, the contact time, oxygen deficit, contact area (bubble diameter), and water temperature.

The self-cleaning action of the flexible membrane occurs when pressure is applied. The rubber membrane flexes outward, until the small slits cut in the face allow the air to bleed through, forming bubbles approximately 2-mm in diameter. The thicker section of membrane in the center provides for more uniform flexing, and also serves as a seal to the air supply system when the supply is turned off. Each time the system is cycled, the membrane flexes, and any biological or chemical accumulation is shaken loose.

Limitations, Constraints, and Trade-Offs. The major disadvantage of gas injection in the tailrace is the poor oxygen transfer efficiency that results due to the relatively shallow depths. In fact, if the diffuser depth is less than 15-feet, alternative aeration approaches should be given priority. Even though the turbulence of most tailraces enhances absorption, the rise time of the injected bubbles is typically short. Absorption efficiency values can range from 5% to 35%, but 20% is typical for a diffuser installation submerged 15-feet (Ref. 6-13, 6-14, and 6-15).

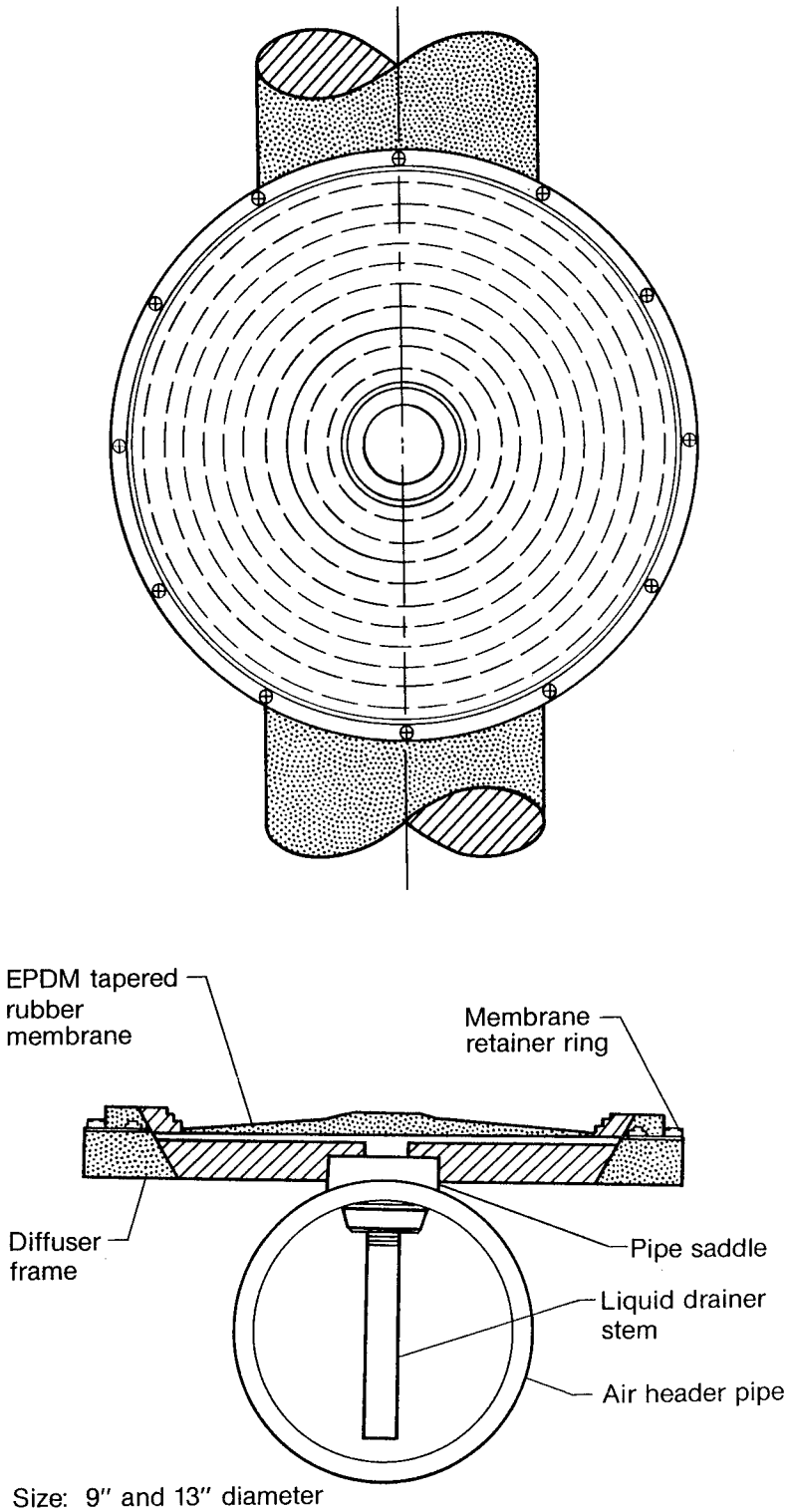


Figure 6-7. Typical Flexible-Membrane Diffuser.

Occasionally, an additional limitation may be lack of sufficient area to install the diffuser array. Because the transfer efficiency is low, considerably larger installations are required in the tailrace than if the same system were to be located in the upstream reservoir.

Another consequence of the poor absorption characteristics is that air is usually the choice of gas to be injected, rather than pure oxygen. Air injection systems require an increase of approximately five times the diffuser array of an oxygen system. As already discussed, the channel may not be favorable to installing such large racks of diffusers.

A particular site may also encounter extremely turbulent flood flows, which could destroy the diffuser array. It may be necessary to incorporate a means of removing the equipment from the tailrace should flood flows become eminent.

Major Obstacles To Installation. Major obstacles to installation could be access to the tailrace, and the overall space requirements for diffuser arrays and compressor installation. If the compressors are driven by electric motors, station power limitations may be a problem.

Environmental Effects. Because the vast majority of the equipment for the aeration system is located below the surface of the tailrace, the initial environmental effect would be associated with the operation of the compressors. Noise suppressors may be required, and the heat resulting from compression may also need to be dissipated in larger installations.

On occasion, nitrogen gas supersaturation may occur due to the injection of air. This may be a problem, depending upon the local fishery. Even though ambient pressures are relatively low and contact time is short, the possibility of supersaturation should be considered, particularly if the discharge is initially near saturation.

Equipment Life Expectancy. Little data exists in hydroelectric applications to predict how often flexible diffusers will require replacement. In waste treatment plants, the membranes require replacement every 2- to 6-years (Ref. 6-13). Under the more favorable conditions typical of tailraces, service life of membranes should be 8- to 10-years.

Compressors require yearly maintenance and periodic overhauls. The life of a particular compressor will depend on the type (rotary lobe, helical screw, centrifugal, axial, etc..), how well it is sized for the application, the frequency of usage (frequency of start/stops), the number of hours used per year, the quality of the maintenance, and the operating environment. Considering all the variables, a compressor in a typical aeration application should last 20- to 30-years, assuming a good maintenance program is followed.

The balance of the aeration system consists of piping, support frames, and controls. Because plastic pipe and hose can be used in this application, the components should last the life of the system, with proper maintenance.

Safety. Due to the low pressures involved, tailrace gas injection is one of the safer techniques to enhance DO levels. Hazardous operations would involve personnel working in the vicinity of air compressors (heat, noise, moving parts), and would occur during the process of placing or removing the diffuser racks.

Modes of Failure. The first mode of failure would likely be an undersized design due to a poor transfer efficiency. Even though systems can be sized according to prior performance in the laboratory, in waste treatment applications, or in other field installations, until the system is installed and tested at the site, transfer efficiency cannot be accurately predicted. The system should be designed to allow for additional expansion should the predicted transfer efficiency not be realized.

The second mode of failure will occur if any single component in the air supply system should break. Distribution manifolds should withstand the forces of the tailrace flows, including flood flows,

and compressors should be maintained to prevent breakdown. Multiple compressors operating in parallel and a backup compressor would improve system reliability.

Risk Analysis. The major risk of a tailrace aeration system is transfer efficiency, because it depends almost exclusively on the interaction of site-specific factors. At a minimum, these factors include depth, flow rate, temperature, oxygen deficit, water quality, turbulence, and age of the aeration system's equipment. Reported efficiencies have been as high as 35%, and as low as 5%. If a tailrace aeration system is installed and does not perform as expected, the only recourse is to either expand the system, or combine it with a second aeration technique. It is also conceivable that sufficient oxygen might be transferred using the unmodified existing system if pure oxygen, or a mixture of pure oxygen and air, is injected rather than air alone.

The second risk of an air-injected tailwater system is nitrogen supersaturation. Measurement of tailwater dissolved nitrogen content should be made prior to any design or installation. If high levels of dissolved nitrogen gas are present, air injection is not recommended. Refer to the Working Example included at the end of this section to estimate if nitrogen supersaturation will occur.

Finally, tailrace aeration systems are very susceptible to damage from flood flows. The high risk of a system being rendered unoperable from the turbulence and debris often eliminates the technique from consideration.

A final risk associated with diffuser/tailrace aeration is the likelihood that the system will be damaged during periods of high flow. Trees, rocks, and boulders can quickly destroy any tailrace installation.

Sizing. Sizing is based most heavily upon an assumed transfer efficiency, but is also affected by site-specific details. These details include oxygen deficit, tailrace depth, and the local topography. The system must be sized to meet the maximum oxygen deficit,

which occurs at maximum hydraulic plant capacity and minimum entering DO levels.

Working Example:

Assumed conditions:

Maximum hydraulic flow:	2,700 CFS
Anticipated depth of diffusers:	25 feet
Minimum powerhouse DO discharge:	0.0 mg/L
Powerhouse dissolved nitrogen discharge:	16.8 mg/L
Discharge DO requirement:	5.0 mg/L
Water temperature:	12°C
Air temperature:	27°C
Elevation of facility:	100 ft (ASL)
Estimated aeration efficiency: (i.e., 20% of the oxygen injected will be dissolved)	20%

Oxygen requirement:

A maximum of 5.0 mg/L of oxygen must be transferred. The maximum oxygen demand is:

$$2{,}700 \frac{ft^3}{sec} * 28.32 \frac{L}{ft^3} * 60 \frac{sec}{min} * 5 \frac{mg}{L} * \frac{1 \text{ pound}}{454{,}000 \text{ mg}} = 50.5 \frac{\text{pounds}}{\text{min}}$$

At a transfer efficiency of 20%, 253 pounds of O_2 per minute must be injected into the tailrace. Because the difference in air density between sea-level and an elevation of 100-feet is very small (see Appendix G), the standard density of 0.07651 pounds/ft^3 will be used. Under standard conditions, air is 20.9% oxygen, or contains 0.01599 pounds of oxygen per cubic foot. Therefore, 253/0.01599 = 15,822 cubic feet of air must be injected into the tailrace per minute. A "safety factor" is generally introduced at this point. The safety factor is meant to provide insurance against undersizing the system by assuming incorrect values for quantities such as transfer efficiency. In this case, a safety factor of 25% will be used, resulting in a required airflow of approximately 19,800 CFM (330 CFS).

Diffuser Array:

The overall initial cost of the system will be greatly affected by the expected amount of air to be supplied by each diffuser. The manufacturer recommends (Ref. 6-15) that 10 SCFM be used per 13-inch diffuser (12 SCFM per square foot of diffuser). Although TVA performed field trials using 9-inch diameter diffusers and preferred a flow rate of 4 SCFM per square foot of diffuser (Ref. 6-16). This

example will compromise, and use 8 CFM per square foot of diffuser, which results in a flow rate of 6.6 CFM per 13-inch diameter diffuser. Therefore, 19,800 ÷ 6.6 = 3,000 diffusers will be required. As more field data is obtained concerning the application, the flow/diffuser can be more accurately estimated. (For more discussion regarding CFM and SCFM, see Appendix G.)

Figure 6-8 is one possible arrangement of the diffuser array in the tailrace. The overall size of the array is approximately 100-feet by 260-feet. Although the equipment was installed in the forebay, Figure 6-9 details the plumbing for one-half of the diffusers attached to a steel frame (detailed in Figure 6-10) that has been used successfully by TVA in the forebay at Douglas Dam in Tennessee (Ref. 6-16). If a similar arrangement were used for diffusers in a tailrace application, additional steps would be required to protect the equipment from flood-flow damage.

Nitrogen Supersaturation:
One approach to estimate the approximate nitrogen increase due to the tailwater diffuser system is to relate nitrogen transfer to oxygen transfer. The integrated gas transfer equation is:

$$\ln(C_s - C_o) - \ln(C_s - C_t) = K_{La} \ \Delta t$$

where:

K_{La} = Overall gas transfer coefficient
C_s = Gas saturation concentration
C_o = Initial gas concentration
C_t = Gas concentration after time Δt
Δt = Contact time in seconds

Using the assumptions for Oxygen transfer, the product $(K_{La})_{ox} \ \Delta t$ can be calculated for the aeration system, where $(K_{La})_{ox}$ is the over-all gas transfer coefficient for oxygen.

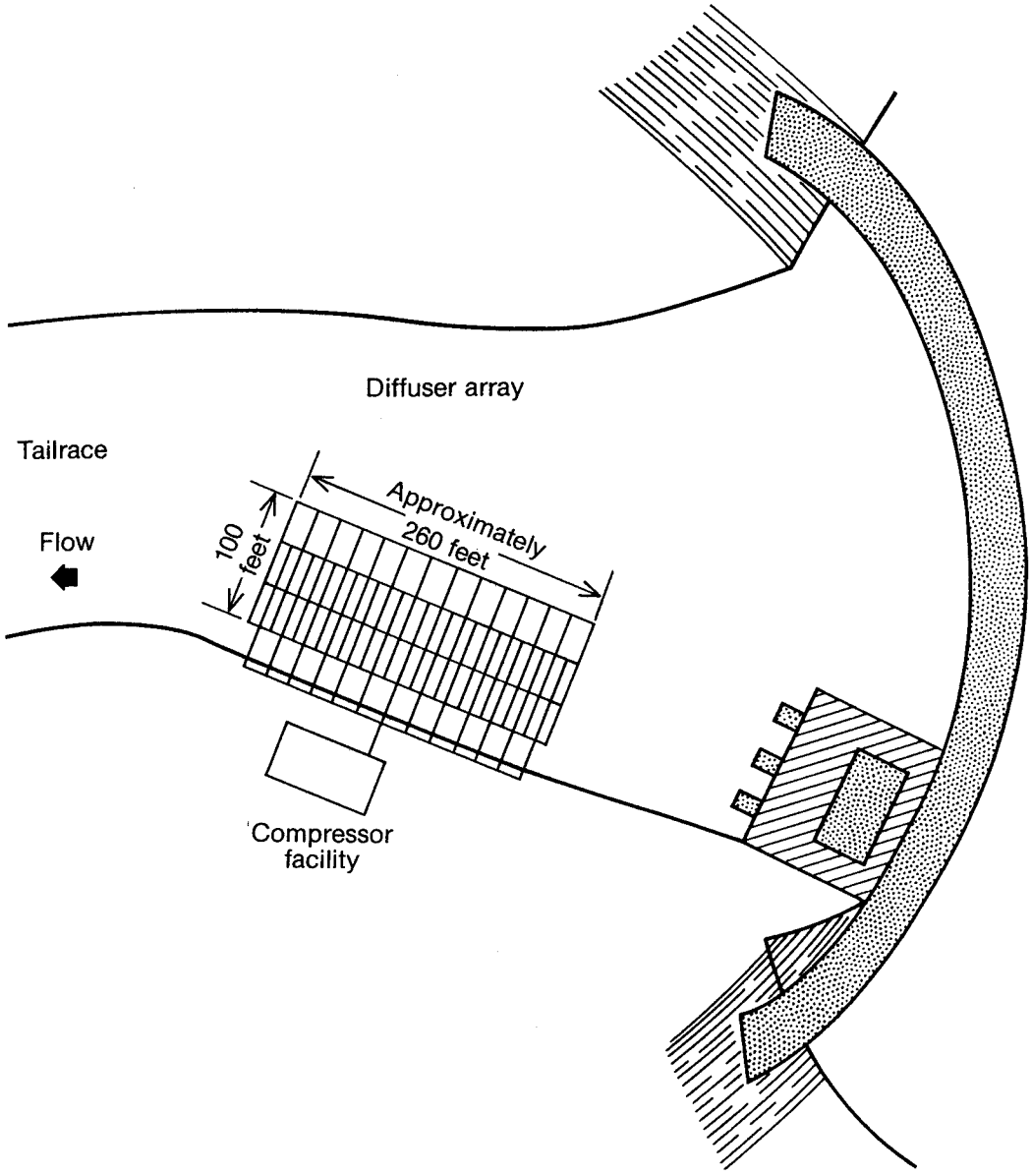


Figure 6-8. Conceptual Layout for Submerged Diffuser Array in Tailrace for Air Injection.

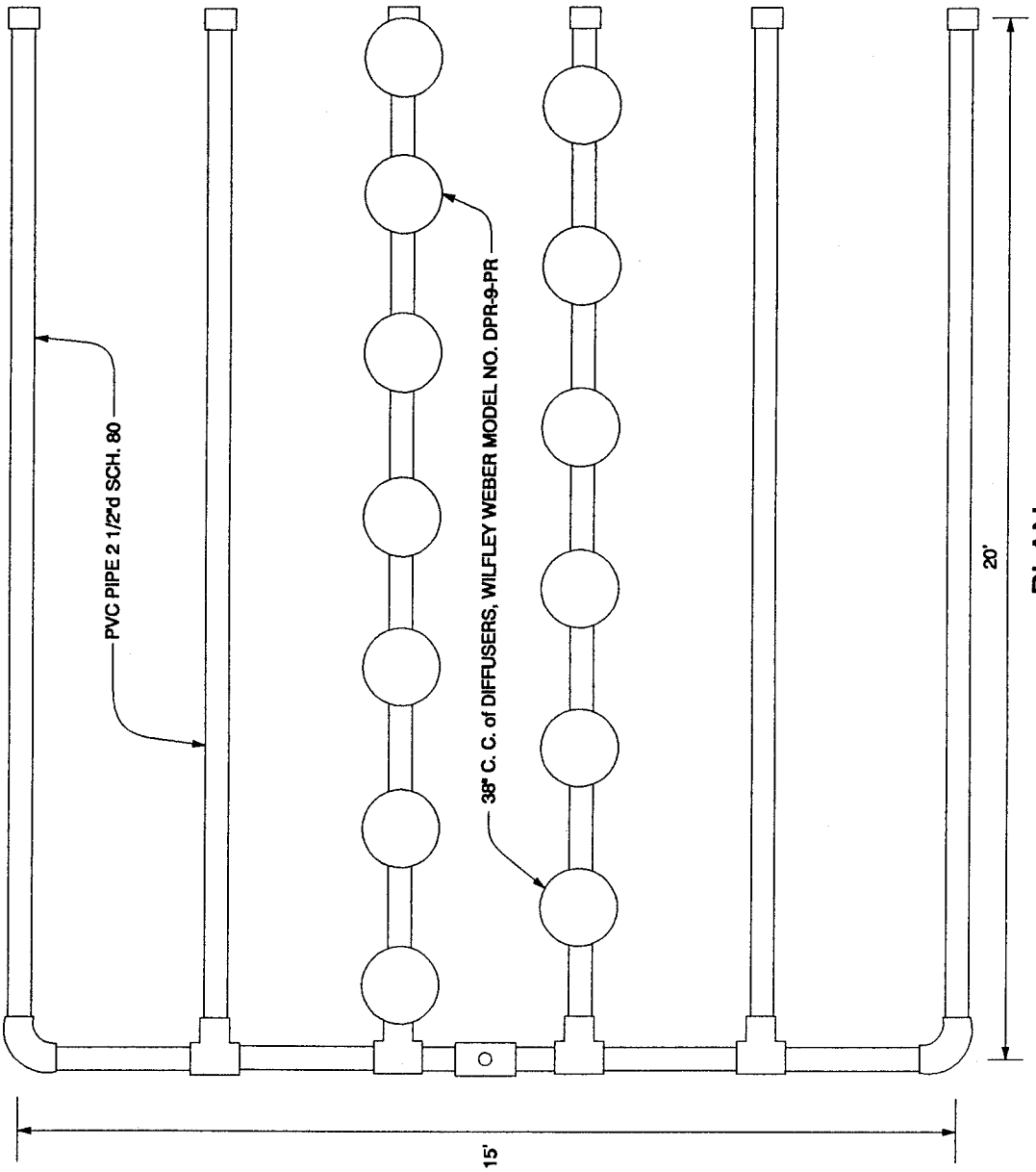


Figure 6-9. Plumbing Detail, Flexible Membrane Diffusers.

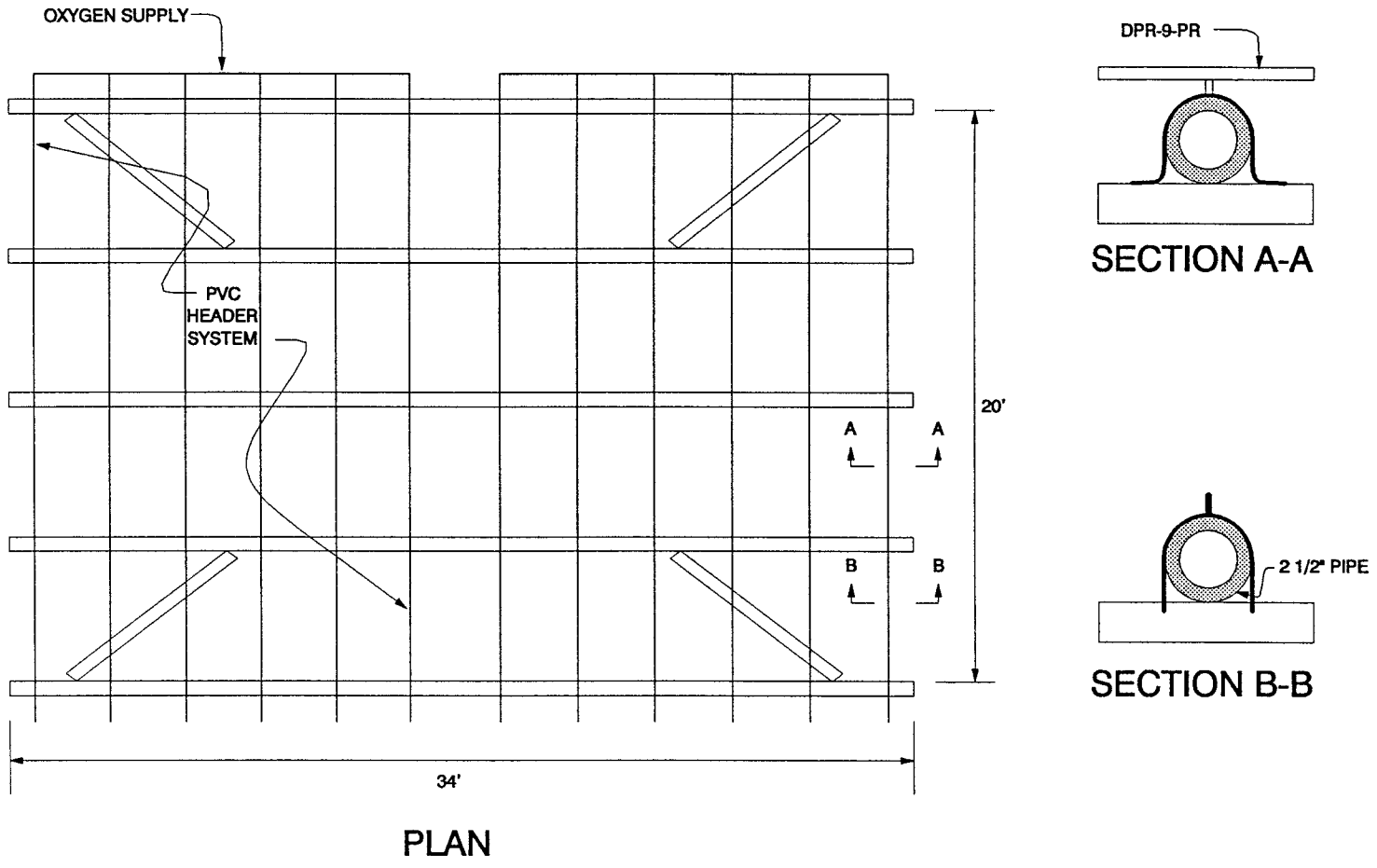


Figure 6-10. Rack Detail, Flexible Membrane Diffusers.

can be back-calculated. Inserting the following values into the above equation:

C_t = 5 mg/L
C_s = 10.77 mg/L (see Appendix G)
C_o = 0 mg/L

$(K_{La})_{ox}\ \Delta t$ is found to be 0.6227. Sheppard, et al., (Ref. 6-17) found that nitrogen transfer was normally 93% that of oxygen, and the same equation could be used to predict the final DN level, provided the 93% adjustment was made. Because the contact time for nitrogen transfer is the same as for oxygen transfer, the following equation can be used:

$$\ln(C_s - C_t) = -0.93(K_{La})_{ox}\ \Delta t + \ln(C_s - C_o)$$

Inserting the following values into the above equation:

$(K_{La})_{ox}\ \Delta t$ = 0.6227
C_s = 24.0 mg/L [3]
C_o = 16.8 mg/L

the dissolved nitrogen level is predicted to increase 3.2 mg/L, or discharge at an average of 20.0 mg/L, somewhat below saturation.

[3] C_s is calculated at the average depth (12.5-feet) and 12°C using Table G-3 and equation G-7.

Compressor size:
Although compressor size is based upon the volume of air that must be moved and the backpressure it must move against, to accurately engineer a compressor system is well beyond the scope of this text. The equations presented here should only be used to estimate the costs of the various components associated with comparing aeration alternatives. If one of the best aeration alternatives involves a large compressor, an expert in designing compressed air systems should be consulted.

The backpressure of a system is defined as the sum of the greatest pressure loss to reach any one diffuser, plus the pressure loss across the diffuser, plus the hydrostatic head. In this example, the hydrostatic head is 20 feet, and the pressure loss across a diffuser is 0.05 PSI (Ref. 6-15), for a total of approximately 9 PSI. The pressure loss of the piping system depends on the design of the distribution system, which includes such items as the length of pipe, pipe size, pipe material, number and type of fittings, operating pressure, and operating temperature. Accurately sizing a compressor combines these items, plus the local barometric pressure, air temperature, and relative humidity. To explain how each of these enters the compressor sizing exercise is beyond the scope of this guide, but Appendix G provides a rudimentary procedure to roughly estimate both piping and compressor size. Because the flow volume is large, to minimize pipe size, the frictional loss in the supply system will be assumed to be somewhat high: 15 PSI. Thus, the supply pressure should be approximately (14.7 + 9 + 15) = 38.7 PSIA. If the air is at 70°F, Appendix G allows us to determine that the supply header will be 12-inches in diameter, and that a total of 2,132-hp are required. To provide system backup and a degree of staging to meet various demand conditions, six 400-hp compressors would be used, each supplying 3,300 CFM of air.

Knowing the supply pressure (approx. 25 PSI) and the airflow (3,300 CFM), Figure 6-11 can be used to select the type of compressor to be used. The figure indicates that large, internal-gear centrifugal compressor will be required.

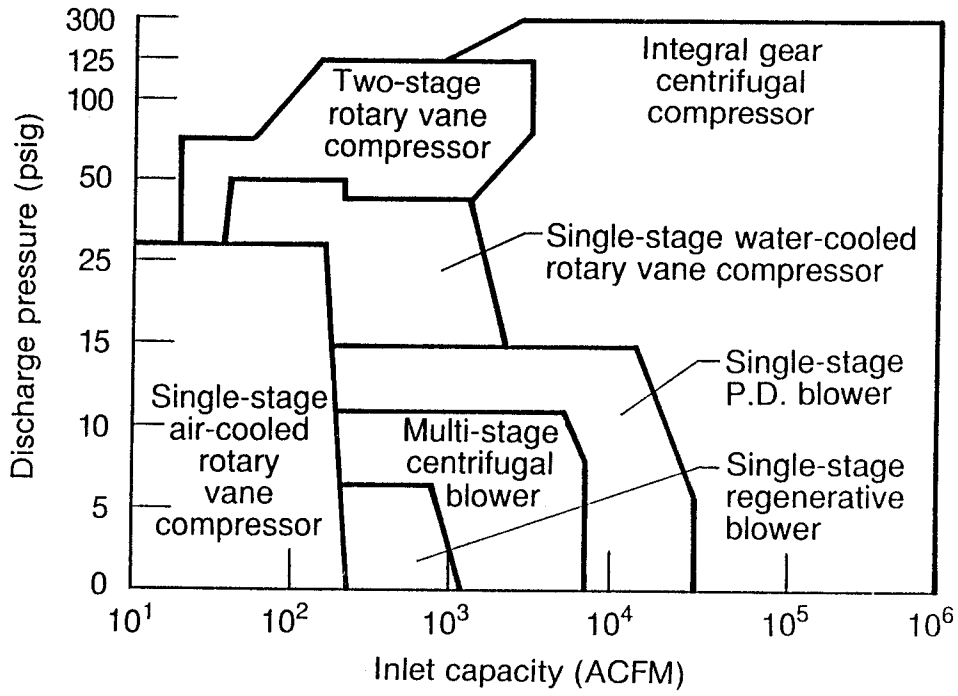


Figure 6-11. Typical performance range (air at standard conditions. (Courtesy of Susquehanna Valley Systems, Inc.)

Because the actual head pressure (less frictional piping losses) against which the compressor must act is only 9 PSI, a more attractive alternative is to use multiple supply headers, reducing the required compressor horsepower. In this case, if two supply headers were used and the frictional head loss was limited to 6 PSI, the calculations would indicate that both headers should be 12-inches in diameter, and that a total of 1,461-hp would be needed. To provide system backup and a degree of staging to meet various demand conditions, four 400-hp blowers would be used, each supplying 5,000 CFM of air.

For most low-pressure applications, either positive-displacement blowers or multi-stage centrifugal blowers will be used. The operating characteristics of the two types are quite different, as illustrated in Figure 6-12. The positive-displacement blower provides a set volume of air over a wide range of backpressures. If sized properly, the machine will be able to counter the effects of any fouling by increasing the delivery pressure. Multi-stage centrifugal blowers allow for throttling of volume (usually by means of a butterfly valve on the inlet or discharge, typically permitting a 30 percent turndown of air volume with only 1 PSI of pressure variation.

Advantages of centrifugal blowers include lower first cost and operating cost in larger (200-hp and above) sizes, and lower sound levels and maintenance costs in all sizes. Single-stage positive-displacement blowers will generally be more efficient, especially below 200-hp, and are capable of discharge pressures to 15 PSIG, where the single-stage centrifugal is not usually effective above 10-12 PSIG. A general rule-of-thumb is to limit consideration of multistage centrifugal blowers to those applications requiring volumes above 2,000 SCFM at discharge pressures less than 10 PSIG.

Maintenance considerations generally favor centrifugal blowers over positive displacement blowers, since centrifugal units frequently operate 75,000 hours without major overhauls, versus only 20,000 or 30,000 hours of operation for positive displacement blowers. The latter are, however, more familiar to most plant maintenance personnel, and are more easily maintained or repaired using readily available parts.

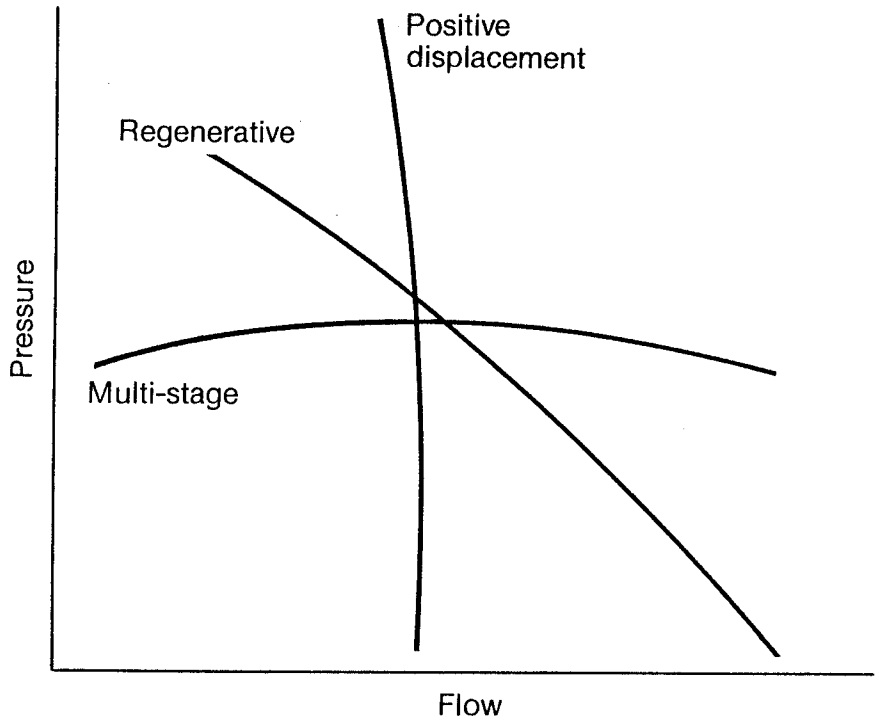


Figure 6-12. Comparative blower performance. (Courtesy of Susquehanna Valley Systems, Inc.)

Costs. Cost of the above example will include equipment, installation, and annual operation and maintenance. Equipment costs can be divided into the diffuser system and the blower equipment. An estimate of the unit price for the diffuser hardware would be $100/- each (1989 dollars), including the diffuser, distribution piping, and the anchoring/support system. Total equipment cost for the diffuser system: 3,000 * $100 = $300,000. Installation labor, estimated at $30 each, would be 3000 * $30 = $90,000.

Blower equipment would consist of four 400-hp positive-displacement units. Table 6-3 lists the approximate installed equipment cost for various types of blowers and compressors. The total cost of the blower installation is estimated to be $320,000. (Note: If sufficient power to operate the compressors is not readily available, the cost of additional electrical components must be considered.)

Table 6-3

APPROXIMATE INSTALLED COST OF AIR COMPRESSORS AND BLOWERS
(Dollars/horsepower)

Multi-Stage Centrifugal Blowers	Two Stage Rotary Vane Blowers	Positive Displacement Blowers	Integral-Gear Centrifugal Compressor
$150	$250	$200	Not Recommended

Summary of installation costs:

Diffuser system hardware:	$300,000
Diffuser system labor:	90,000
Compressor installation:	320,000
Subtotal:	$710,000
Engineering (10%):	71,000
Total:	$781,000

To determine the annual costs, it will be assumed that the system will operate 5-months of the year, the facility generates 6-hours per day, and the average oxygen deficit per month is:

Month 1: 2 mg/L
Month 2: 4 mg/L
Month 3: 5 mg/L
Month 4: 5 mg/L
Month 5: 4 mg/L

Annual operating costs include labor, maintenance, energy, and insurance. If the life of the system is assumed to be 30-years, insurance is calculated as 1/30th the installation cost, less engineering fees. Labor costs will be assumed to be 1-operator, 24-hours per day at a rate of $30.00 per hour, or $108,000 (5-months = 150 days; 150 days * 24-hours * $30.00).

The life of the diffusers will be assumed to be ten years. Installed, replacement cost will be $70.00 each, or an expenditure of $210,000 at the end of 10- and 20-years.

Using published data (Ref. 6-18), annual compressor maintenance can be valued at $9.00 per horsepower, per year, for units in typical industrial installations. Using the oxygen deficit and operational schedule above, however, the compressors will only operate a total of 3,960 hours, or an average of 990 hours each, or 11.3% of the time per year. If a well maintained industrial compressor costs $9.00 per horsepower per annum to maintain, and would generally have a 50% duty cycle, the compressors in this application could be expected to incur a maintenance cost of (11.3 ÷ 50) * $9.00 = $2.03 per horsepower to maintain. The total annual compressor maintenance cost would be $3,248.

Annual energy costs for operating the compressors can be calculated using the estimated number of operational hours arrived at above. When operating at full load, each of the 400-horsepower compressors draw 300 kilowatts. Because the compressors are expected to run a total of 3,960 hours per year, the power consumed is 1,188 MWh. With power valued at $0.06/kWh, the yearly operating cost of the compres-

sors is $71,280. (Note: If electrical demand charges are levied, they should be added.)

The total annual operating cost will be:

Insurance (1/30th of initial cost):	$23,667
Annual Compressor Maintenance:	3,248
Labor:	108,000
Energy costs:	71,280
Total:	$206,195

The Present Worth of a 30-year series of annual costs of $206,195 at 12% interest is $1,660,900. The periodic cost of membrane replacement must be converted to its Present Worth value:

First membrane replacement:	
Present Worth of $210,000, ten year period, 12% interest rate:	$67,620
Second membrane replacement:	
Present Worth, 20-year period:	21,777
Total:	$89,397

Thus, the total Present Worth of using air diffusers in the tailrace is:

Initial installation:	$781,000
Present Worth, annual operations:	1,660,900
Present Worth, periodic maintenance:	89,397
Total Present Worth:	$2,531,297

($314,252 per annum for 30-years at 12%)

For a cost comparison, a pure oxygen-supplied injection system will be sized for the same site assuming the same gas transfer efficiency (i.e., 20% of the oxygen injected is absorbed). Because pure oxygen rather than air is being injected, the overall size of the diffuser array can be reduced by 80% and the compressors can be eliminated. Using the same 25% safety factor, the oxygen system will only require 575 diffusers.

Annual insurance and labor costs will also be reduced. However, additional costs will be incurred as a result of purchasing commercial oxygen, and leasing the storage tanks and vaporizers. Using the same operating and oxygen deficit schedule, 5,459 tons of pure oxygen would be required for a typical year. Note that the oxygen estimate is based upon a typical operating schedule for the facility (6-hours per day). If changes in the schedule are likely, such as periods of 24-hour generation during flood flows, additional operating costs should be considered for the aeration system (both the air-injection and the oxygen-injection system). However, particularly during periods of flood-flow, if spillage occurs simultaneous to generation, the mixed flow downstream of the facility will probably be at a dissolved oxygen level sufficient to meet state water quality standards.

Installation Costs:

Diffuser system, hardware: (575 diffusers, $100 each)	$57,500
Diffuser system, labor: (575 diffusers, $30 each)	17,250
Site work for oxygen equipment:	10,000
Subtotal:	$84,750
Engineering (10% installation cost):	8,475
Total:	$93,225

Annual costs will include the purchase of oxygen, and the leasing of storage tanks and vaporizers. Because no mechanical equipment is involved, labor to operate the system would consist of manually varying the flow rate to meet the demand. This process could also be automated. If an operator checks the DO level twice a day during the operation of the plant, and adjusts the oxygen flow rate to meet the

demand, one hour may be spent, or $30.00 per day. The annual cost of labor, therefore, for the 5-month effort is $4,500.

Annual costs:

Insurance (1/30 installation)	$2,825
Labor:	4,500
Oxygen purchase ($75/ton):	409,425
Lease oxygen equipment:	13,200
Total:	$429,950

The Present Worth of the above annual cost over a 30-year period at 12% interest is $3,463,247.

The membranes will still require replacement every ten years, but the smaller number of diffusers are less expensive. Replacing 575 diffusers at $70.00 each would cost $40,250.

Membrane replacement, Present Worth of $40,250, 1st ten year period, 12% interest rate:	$12,961
Membrane replacement, Present Worth, 20-year period:	4,174
Total:	$17,135

Thus, the total Present Worth of using pure oxygen in the tailrace is:

Initial installation:	$93,225
Present Worth, annual operations:	3,463,247
Present Worth, periodic maintenance:	17,135
Total Present Worth:	$3,573,607

($443,628 per annum for 30-years at 12%).

The total Present Worth of using the pure oxygen-injection system is 41% more than the air-injection system. It is also worth noting that a considerable difference exists in the amount of capital that must be expended for initial installation. The air-diffuser system includes compressors, and costs $781,000 to install. The oxygen system does not involve compressors, and is estimated to cost $93,225. However, the estimated annual expenditure for the air-

diffuser system is $206,195, as compared to $443,628 for oxygen injection.

The oxygen injection system has no effect on power generation, and incurs no energy costs. The electrically-driven compressors of the air-diffuser system not only consume power, reducing revenues, but also reduce the total effective generating capacity of the powerplant. Although the generator still produces the same amount of power, a portion of it must be reserved to operate the compressors.

Case History. No actual case histories are known to exist where diffusers have been permanently installed in hydroelectric tailraces for the purpose of DO enhancement. Certain installations are known to exist that were purely experimental, but early failure of the equipment to withstand the high turbulence caused other techniques to be considered.

Documentation does exist that describes diffuser tests in large rivers for aeration purposes. One system was tested in the Delaware River near Philadelphia during 1969 and 1970 (Ref. 6-64), and determined that induced river aeration systems were more economical at improving DO levels than advanced waste treatment plants. A 250 hp diesel compressor supplied air to the diffusers at pressures up to 25 PSIG. The supply line connecting the diffusers, located approximately 200-feet away, was 12-inches in diameter. Air from the supply line was divided into two 8-inch branch lines leading to two 8-inch underwater headers, 5-feet apart and 80-feet long. A total of 160 diffusers were used, (Link-Belt 3/4-inch adjust-air diffuser nozzles) each having 12 openings 5/32-inch in diameter.

One problem the project encountered when measuring the aeration effect was that the site was a tidal estuary, with water flowing upstream for about 12-hours each day. As such, data was only taken during periods of the out-going tide, which necessitated that the data be taken at different times during the day.

Operating under these conditions, and with some additional slight modification, the testing revealed that by varying the depth of the diffusers over a range of approximately 13-feet to 38-feet, oxygen absorption efficiency ranged from 1% to slightly more than 12%. Efficiencies at a depth of 13-feet were 1% to 6.5%; at the 25-foot depth, 4.2% to 8.2%; and, at the 38-foot depth, 1.8% to 12.3%. The study concluded that in spite of the increased transfer rates encountered at the greater depths, the most economical transfer in terms of pounds of oxygen per horsepower-hour were obtained at the shallower depths. It should be reiterated that the diffusers used in this study were of the coarse-bubble type.

Tailrace Aeration / Surface Aerators

Physical Aspects. Although surface aerators may be familiar to most hydro owners, many are unfamiliar with the aspirating-propeller type surface aerator. Although the aspirating-propeller aerator has been in use for over 50-years, it has only been recently considered as a viable alternative to aerate tailraces. In the past, other types of aerators have been considered for tailrace aeration (Ref. 6-20 and 6-21), but were quickly eliminated due to the high energy consumption, low aeration efficiency, the large number of units required to meet a small deficit, the maintenance problems, and the negative audible and visual environmental impacts. Aspirating type aerators, however, have improved significantly in these areas, and should be considered for smaller flow volumes, or large flows with small deficits.

The physical aspects of aspirating aerators are similar to other surface aerators. However, with sizes that range from fractional horsepower up to 100 horsepower, far fewer units are required. As illustrated in Figure 6-13, the aerators are mounted on floats, and anchored in the tailrace. The motors are mounted at an angle to the water surface, directing a current of air and water downward, providing a strong mixing current. Because of the mixing characteristics



Figure 6-13. Application of an Aspirating-Type Surface Aerator

and the variations in oxygen deficit that hydroplants encounter, several units (two or more) would act in parallel across the width of a tailrace. When aeration is not needed, or when flood flows threaten the installation, the units could be withdrawn.

Working Principles. Figure 6-14 illustrates a typical aspirating-type surface aerator. The unit consists of an electric motor, a shaft enclosed in a concentric pipe vented to the atmosphere, and a submerged propeller. As the propeller turns, it forces water across the bottom of the shaft enclosure, creating a vacuum of 35- to 45-inches of water. The vacuum draws in air, and the action of the propeller forces it down into the water. The unit is usually mounted at a 25- to 30-degree angle to the water surface. The mixing action in combination with the depth provide up to twice the oxygen transfer efficiencies of more typical surface aerators.

Limitations, Constraints, and Trade-Offs. Surface aerators can be expected to add 2 to 3 mg/L to a flowing body of water. If greater deficits exist, other aeration systems should be considered either as stand-alone alternatives or in combination with aspirating surface units. If the tailrace is shallow (<10-feet), surface aerators will not perform efficiently, and may re-suspend bottom sediment.

Major Obstacles To Installation. If the oxygen deficit or flow is large (i.e., flow > 2,000 CFS; deficit > 3 mg/L), considerable surface area may be required for the aeration units to operate efficiently. Table 6-4 is the minimum horizontal spacing recommended by Aeration Industries for their aspirating aerators. If the units are crowded, plume interference may occur, reducing oxygen transfer.

Table 6-4

HORIZONTAL SPACING FOR ASPIRATING SURFACE AERATORS

Horsepower	Minimum Horizontal Spacing
10	10 Feet
20	15 Feet
50	20 Feet
100	30 Feet

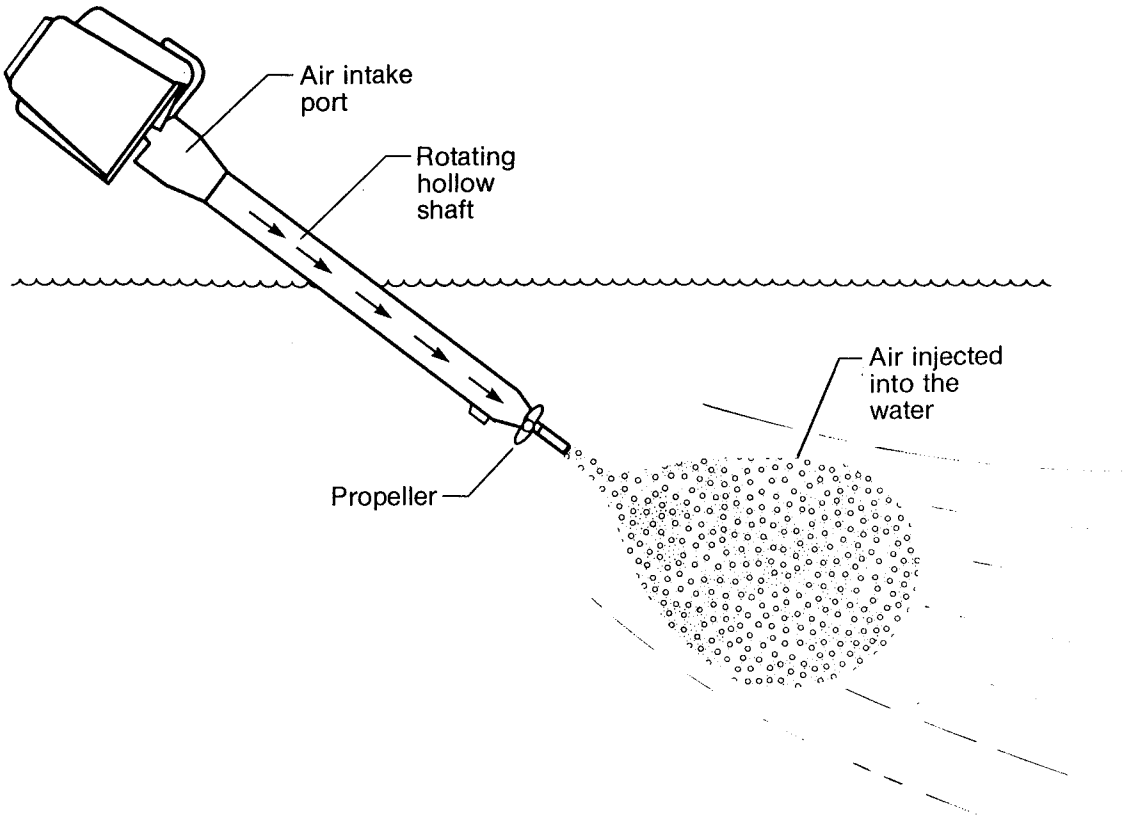


Figure 6-14. Typical Aspirating-Type Surface Aerator.

Additional obstacles to installation may include shallow tailraces (less than 10-feet), or the fact that both the flow and the deficit are large, requiring an excessive number of units.

Environmental Effects. The main problems with all surface aerators is noise and visual impact. With the aspirating-type aerators, larger sizes have lessened visual impact by reducing overall numbers, and improvements to design has produced quieter units.

Another environmental effect that may occur if the system is not designed and installed properly is increased downstream turbidity due to re-suspension of bottom sediments. If aerators are operated in water greater than 15 feet in depth, increased turbidity should not occur.

Equipment Life Expectancy. Because the aeration units are generally used less than 6-months per year, are only used during periods of generation, and are removed and stored each year, a life expectancy of 20-years or more can be expected, provided they are maintained properly. Generally, maintenance consists of periodic bearing replacement.

Safety. Since the aerators are electrically operated, electrical shock may be a hazard. In addition, if the tailrace immediate to the discharge is accessible to recreationists, safe boating and fishing practices must be exercised.

Modes of Failure. The units should be "banked" by design, allowing their operation to be staged, depending upon the flow and DO deficit. Unless the facility is discharging at full capacity and the oxygen deficit is at a maximum, failure of a single unit should not drastically impact overall water quality. However, should a failure occur under these conditions, a reduction in discharge may be necessary until a replacement aerator can be floated into place.

If the units are not removed seasonally, it is conceivable that flood events could destroy the anchoring system and, in turn, destroy the floating aerators. To eliminate this possibility, the anchoring

system could be such as to allow the aerators to be guided to shore and removed prior to flood flows being released.
Finally, a power outage, although unlikely, would also render the system inoperative.

Risk Analysis. Because the units are regularly applied to waste treatment and aquaculture systems, their performance is more predictable than other aeration techniques. However, with few exceptions, previous applications have been in relatively slow- or non-moving bodies of water. The velocities typical of most hydroelectric plant tailraces may effect the transfer efficiencies of the aeration units. Field tests for this technique would not be expensive, and are recommended.

Sizing.

Working Example:

Assumed conditions:

Maximum hydraulic flow:	1,000 CFS
Depth of tailrace:	20 feet
Minimum powerhouse DO discharge:	0.0 mg/L
Discharge DO requirement:	5.0 mg/L
Water temperature:	12°C
Air temperature:	27°C
Elevation of facility:	1,000 ft. (ASL)

Oxygen requirement:

A maximum of 5.0 mg/L of oxygen must be transferred. The maximum oxygen demand is:

$$1000 \frac{ft^3}{sec} * 28.32 \frac{L}{ft^3} * 60 \frac{sec}{min} * 5 \frac{mg}{L} * \frac{1 \text{ pound}}{454{,}000 \text{ mg}} = 18.7 \frac{\text{pounds}}{\text{min}}$$

Because the depth of the tailrace is greater than 15 feet, aspirator-type surface aerators can be consider without the risk of increased turbidity from upsetting bottom sediments, and the mixing of the air and water will be maximized.

Surface aeration systems are rated according to a Standard Aeration Efficiency (SAE), which is their ability to transfer oxygen under the standard conditions of 20°C, sea level, and the receiving water containing 0.0 mg/L of dissolved oxygen. Because the saturation level of oxygen under these conditions is 9.1 mg/L, the DO deficit is

also 9.1 mg/L. (Ref. 6-22). These conditions are similar to those often encountered initially in hydroelectric discharges, but the transfer efficiency of oxygen will decrease significantly as the water is aerated and the oxygen level begins to increase. The SAE will no longer apply in situations where the initial DO level is not 0.0 mg/L, but must be calculated under the new field condition. Transfer efficiency under any set of field conditions is calculated by the following equation (Ref. 6-22):

$$N = N_0 \left(\frac{(C_{walt} - C_L)}{9.1} \right) (1.024)^{T - 20}$$

where:

N = oxygen transfer under field conditions (lbs O_2/hp)
N_o = oxygen transfer under standard conditions (lbs O_2/hp)
C_{walt} = DO saturation of water at given altitude (mg/l)
C_L = operating DO (mg/l)
T = Temperature °C (°C)

Boyd determined the SAE (N_o) for the aspirating type aerator averaged 2.6 pounds of O_2 per horsepower-hour. However, the tests were conducted in small ponds (0.1 or 0.25 acre). More recent results of similar tests conducted in a tailrace (Ref. 6-23) indicate that an SAE of 2.0 pounds per horsepower-hour more accurately predicts the oxygen transfer.

The final quantity needed to determine the actual field transfer efficiency of the aerator is C_{walt}. Appendix G indicates the DO saturation at 12°C and sea level is 10.77 mg/L. For an elevation of 1,000-feet, Table G-1 indicates an Altitude Correction Factor of 0.95 should be used, resulting in a C_{walt} of 10.23 mg/L. Thus, the initial field oxygen transfer efficiency with a 0.0 mg/L DO level can be predicted to be:

$$N = 2.0 \times \left(\frac{(10.23 - 0.0)}{9.1} \right) \times (1.024)^{(12 - 20)} = 1.86 \ \frac{\text{lbs } O_2}{\text{hp-hr}}$$

When the DO in the tailrace reaches 5.0 mg/L, the oxygen transfer efficiency will be:

$$N = 2.0 \times \left(\frac{(10.23 - 5.0)}{9.1}\right) \times (1.024)^{(12 - 20)} = 0.95 \frac{\text{lbs } O_2}{\text{hp-hr}}$$

The average oxygen transfer efficiency for this application will be (1.86 + 0.95)/2 = 1.41 lbs O_2/hp-hr. Because the oxygen deficit is 18.7 lbs/min, or 1,122 lbs/hr, a total of 796 horsepower will be required.

Cost. Eight 100-hp units could be used to address the situation just described. The installation would include the purchase of the units, an anchoring system, and the electrical supply. The equipment cost of aspirating-type aerators is approximately $477/hp, and installation costs can be estimated to equal equipment costs (Ref. 6-24). The combined total would be ($477 * 800) * 2 = $763,200.

Annual costs include maintenance, labor for placement and removal each season, minimal labor to verify operation on a daily basis, insurance, and electrical power costs. Maintenance can be provided by the manufacturer at an annual cost of 5.6% of the installed price (plus travel expenses), or estimated at $18 per horsepower per year, plus labor, if the owner prefers to perform the maintenance. This example shall assume that the owner performs the maintenance, and that 8-man-hours are required per unit per year. For the 8 aerators, the annual maintenance cost would be ($18/hp-yr * 800 horsepower) + 8 * (8 man-hours * $30/hr) = $16,320.

Depending upon the configuration of the tailrace and the design of the anchoring system, it will be assumed that seasonal installation and removal will require a total of 150 man-hours. Operation would consist of an operator periodically examining the downstream DO conditions during periods of generation, and turning the aerators on or off as needed. Assuming a stratification period (5-month) and operational scheme identical to the one described for gas injection in the tailrace, the operation of the aerators should not require

more than 30 minutes per day, or $2,250 per year using a rate of $30.00 per hour. Because the units only operate 6-hours per day, and are removed from the tailrace seasonally, life expectancy will be assumed to be 30-years.

Annual energy costs will be based upon the operational schedule. With eight units available, a flexible staging program to meet the oxygen demand will be very cost effective. Because the ability of the units to transfer oxygen depends upon the deficit, the oxygen transfer efficiencies must be re-calculated for each month, depending upon the specific conditions. Using the oxygen demand schedule from the gas injection example and the procedure outlined above for determining the oxygen requirement and the oxygen transfer efficiencies, the following number of units would be required to operate during the stratified period:

Month	Deficit	Lbs O_2/hr Required	Avg. Oxygen Trans. Eff.	No. of Units Operating
Month 1:	2 mg/L	449	1.13	4
Month 2:	4 mg/L	898	1.31	7
Month 3:	5 mg/L	1,122	1.41	8
Month 4:	5 mg/L	1,122	1.41	8
Month 5:	4 mg/L	898	1.31	7

The total number of hours of operation for the eight units is 6,120. The power consumed by each aerator is 53.4 kW. When all aerators are operating, the demand is 427 kW. The annual cost to operate the aerators using $0.06/kWh is $19,608.

The total annual operating costs are estimated to be:

Insurance (1/30th of initial cost):	$25,440
Annual Maintenance:	16,320
Labor:	2,250
Energy costs:	19,608
Total:	$63,618

The total Present Worth of using aspirating-type surface aerators in the tailrace is:

Initial installation:	$763,200
Replacement Generation Capacity:	512,443
TOTAL PRESENT WORTH:	$1,275,643

($158,366 per annum for 30-years at 12%)

Case Study. During the summer of 1989, Dr. Richard E. Price applied aspirating-type surface aerators to the discharge of the stratified Lake Texoma, along the border of Texas and Oklahoma. Although the facility normally discharges 10,000 CFS when generating, the object of the tests was to determine the viability of using surface aerators to raise the tailwater DO level during periods of non-generation. During these periods, the house generator passes 25 CFS, and gate leakage adds another 50 CFS. Leakage water is normally at 0.0 mg/L DO and 21°C. The house generator is fitted with a vacuum breaker, which is allowed to remain open to the atmosphere during operation, which normally increases the DO level of the small discharge by 3.5 mg/L. The tailwater immediately downstream of the powerhouse is approximately 30-feet deep, but is reduced to less than 2-feet deep a short distance downstream.

Dr. Price's experimentation involved various arrangements of two 5-hp aerators and one 10-hp unit. Tests were conducted during periods of non-generation, and were directed at determining overall transfer efficiency, and optimum orientation of the units.

Preliminary results indicate that with the vacuum breaker of the house unit vented to the atmosphere, the downstream DO level of the mixed flows (house generator and leakage) was approximately 1.8 mg/L, with no aerators operating. By operating a single 5-hp unit, the DO rose to 2.0 mg/L. By using a total of 15-hp, the downstream discharge was 2.6 mg/L. Dr. Price also found that the best results were obtained when the aerators were oriented to discharge at a 90° angle to the main flow. He also recommends that for this type of application, an oxygen transfer of 2.0 lbs O_2/HP.hr be used rather than 2.5 lbs O_2/HP.hr, as recommended by the manufacturer.

The Corps of Engineers (Vicksburg, MS) has recognized the benefits of the application, and has decided to proceed with the installation of

a single 75-hp unit, to be installed during the summer of 1990. The design will include a system to allow the aerator to be deployed during periods of non-generation, and removed just prior to the 10,000 CFS generation flow. (Ref. 6-23)

6.2 POWERHOUSE TECHNIQUES

Epilimnion Surface Pumps

Physical Aspects: For the aeration of hydroelectric discharges, epilimnion surface water pumps consist of a floating platform generally fixed to the dam or tied off to the shore, upon which is mounted a diesel or electric motor connected to a submerged impeller. Figure 6-15 is a schematic representation of a typical system, and Figure 6-16 is a photograph of TVA's test system being installed at Douglas Dam in Tennessee.

Surface water pumps are axial flow devices usually 6- to 15-feet in diameter. The pumps are gear-driven by a relatively small motor, usually less than 50-hp. The pump impeller is positioned about one impeller diameter below the water surface and is rotated at a relatively low speed. The pumps are typically capable of moving large quantities of water (several hundred cubic feet per second) at a relatively low velocity (2- to 5-feet per second).

Working Principles: The purpose of the pumps is to move warm epilimnetic (surface) water, high in dissolved oxygen content, downward into the withdrawal zone of the hydroelectric turbine as shown in Figure 6-15. The water moved by the pumps mixes with a portion of the poorer quality hypolimnetic water that is normally released, thus improving the DO content of the facility's discharge.

To reach the withdrawal zone of a hydroelectric turbine in a stratified reservoir, the pump must provide enough momentum to overcome the buoyant forces acting within the reservoir. The stratification of the reservoir causes a buoyancy force to act on the pumped plume due to the replacement of the cold hypolimnetic water with warmer, lighter, epilimnetic water. The water moved by the pump acts like a buoyant plume, tending to float back to a layer of similar density.

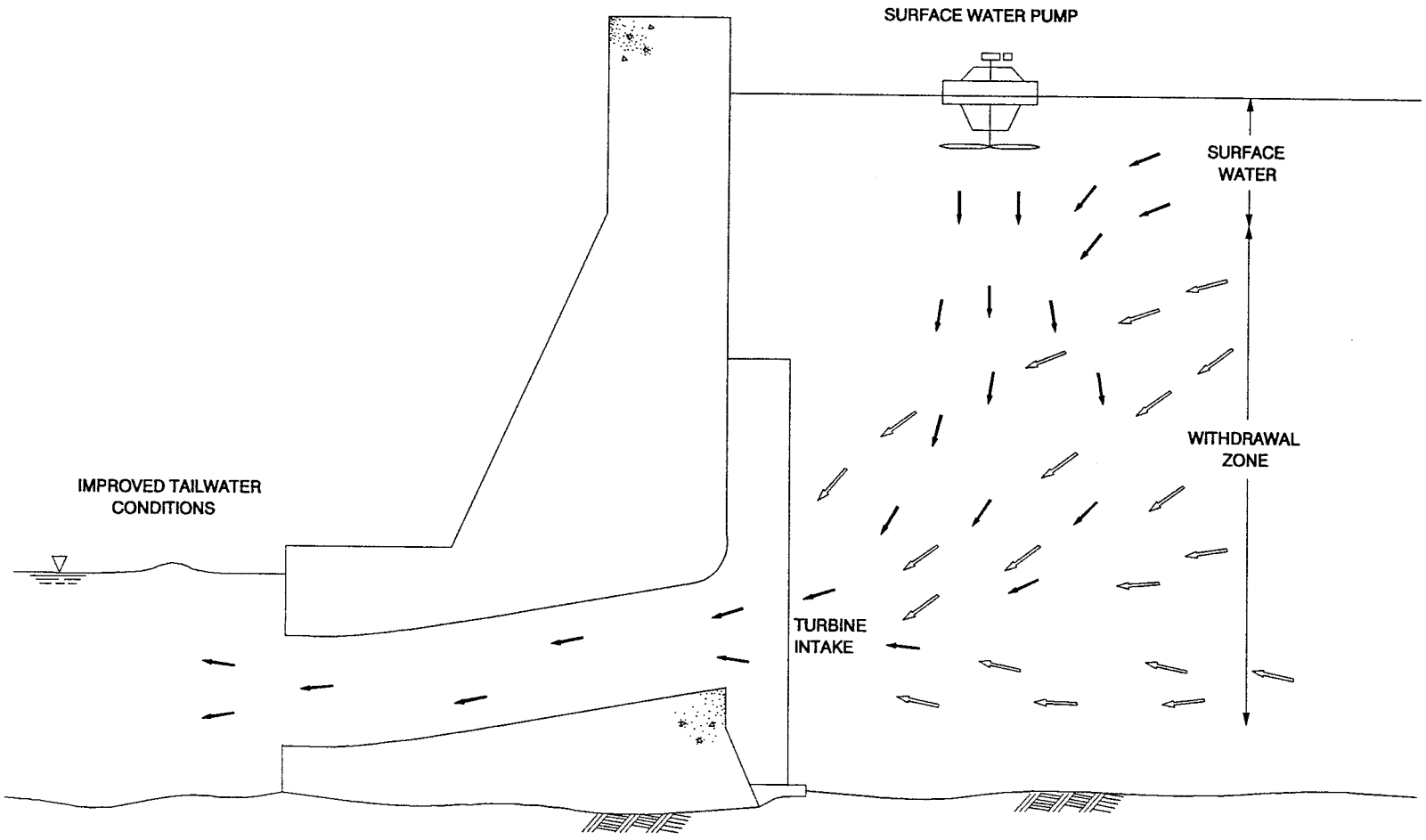


Figure 6-15. Typical Surface Water Pump Application.

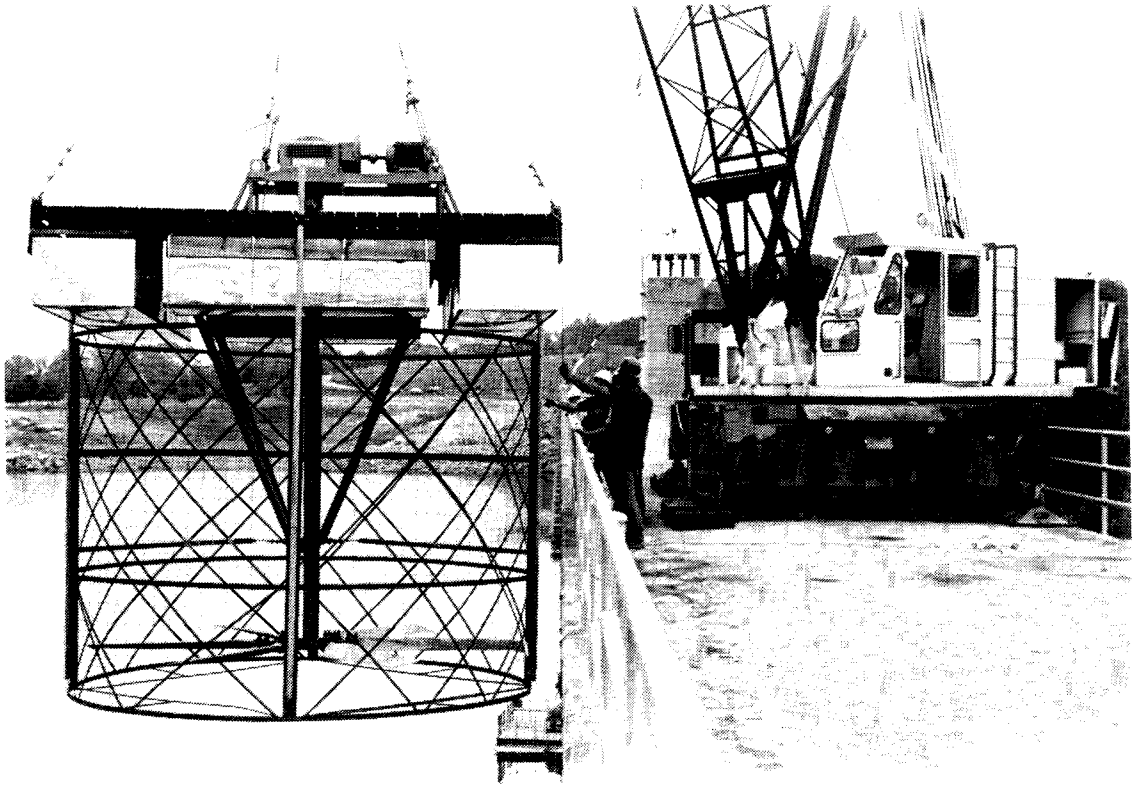


Figure 6-16. Installation of Epilimnion Surface Pump at TVA's Douglas Dam

Limitations, Constraints, and Trade-Offs. The performance of the surface water pumps is dependent on and limited by the reservoir conditions. A low DO content in the epilimnion, or a strongly stratified reservoir will limit the effectiveness of a given pump operation. The epilimnetic DO content is a function of the effects of sunlight, wind and nutrients on the algae population in the epilimnion. In TVA's Douglas Reservoir, a seasonal period was observed when the BOD of decaying algae caused a DO-depressed water layer to form just below the epilimnion. Due to the entrainment of this low DO water, operation of the surface water pumps actually decreased the DO content of the release.

Because the effectiveness of the pumps is based on the dilution of the release, this method is most efficient when there is a large difference in the DO available in the epilimnion and the DO content of the normal release. Likewise, as the epilimnion DO level approaches that of the desired DO in the discharge, the required volume of pumped flow increases.

A sometimes undesirable side-effect of operating a surface water pump system is the increase in the temperature of the release due to the addition of the warmer epilimnetic water. This temperature increase could be detrimental at hydroprojects that support cold water fisheries or powerplant cooling systems downstream. The amount of temperature change can be estimated using the dilution formulas presented later in this section.

Another potential limitation is over-penetration. The pump output velocity required during periods of strong stratification may exceed that required during periods of weak stratification. The excess velocity will cause the plume to penetrate to the bottom of the reservoir. Over-penetration can stir up sediments causing increased turbidity in the release and other potential problems. Over-penetration is also an indication of energy wasted in supplying the pumped water velocity. A potential solution is to use the pumps with variable speed drives. This allows specification of the output velocity to meet prevailing conditions. However, any decrease in output velocity is also a decrease in the total output of the pumps ($Q = V * A$).

Major Obstacles To Installation. Installation of the pumps requires a means to launch the floating platforms, a power supply, power cables and positioning connections. Each of these requirements can determine whether or not a surface water pump installation is suitable at a particular site.

In general, surface water pumps are large and unwieldy. The assembly and launching of a large diameter pump can be a problem because the impeller is located about one diameter under the floating platform. This requires a temporary scaffold to support the pumps during assembly. Assembled units require a crane to lift them from the scaffold, to move the units into position, and to lower them into the reservoir. This can be a hazardous and costly undertaking, that requires a suitable area for assembly, room for the crane to operate, and a suitable location for lowering the pumps into the reservoir. At some sites all of the work can be done from the deck of the dam. Working on the deck of the dam, however, requires extra precautions due to the height of the working area, limited maneuvering room for the crane, and point loadings on the deck.

An alternative approach that may be used with smaller pumps (less than 10-feet in diameter) is to launch the pumps from a trailer at a boat ramp. This requires a frame on either the flotation platform or the trailer to support the unit. The 1989 installation at TVA's Douglas Dam includes a variation of this approach. For this design, the impeller shaft slides vertically through the speed reducer so that the platform can be launched with the impeller pulled up within a few feet of the bottom of the platform. The impeller and shaft can then be lowered into position in the water before operation. This design will also be used to launch pumps up to 15-feet in diameter.

Surface water pumps have been installed and tested with both internal combustion engines and electric motors. Electric motors are more suitable for permanent installations due to simpler control systems and reduced maintenance, but require a suitably sized electric power supply. Often, an auxiliary electric circuit can be used, but should the power requirements exceed the available capacity, a dedicated power supply or modifications to the switchyard may be required. These items may make the project prohibitively expensive.

Electric cables from the power supply to the pumps must be capable of handling reservoir pool level fluctuations. At Douglas Dam where the pool level may change as much as 60-feet, cable reels were used to take up the slack in the cables as needed.

Holding the pumps in position requires a system of cables and/or stifflegs. The positioning system must be designed to handle the forces generated by the starting torque of the motors, the forces due to wind and wave action, and the full range of headwater elevation changes. The pounding forces due to waves and boat wakes have proven to cause the most detrimental loadings on the positioning systems.

Environmental Effects. Adverse environmental effects from the pumps are minimal. The electric motors and drives are generally very quiet and cause no objectionable noise. However, the operation of the pumps may adversely affect the environmental water quality of the river downstream of the project, particularly if the area is sensitive to temperature increases or suspended solids. The temperature increase is a function of the reservoir conditions and an unavoidable effect of diluting the turbine release with warmer surface water. The temperature increase and its potential effect on the tailwater, however, can be estimated before installation. The effects of an increase in suspended solids due to over-penetration of the pump plume is difficult to predict but can be avoided by careful operational changes. The amount of over-penetration, location of the pumps, and type of sediments all impact the amount of increase in the suspended solids. The chemical make-up of the sediments may also effect the tailrace should there be pollutants or strong chemical concentrations present.

Equipment Life Expectancy. The life expectancy of a surface water installation depends on the type of equipment installed and site-specific weather conditions. Most commercially available mixers have a 10-year life expectancy under typical conditions.

Safety. Safety considerations for the pumps must include concern for the high voltage power cables, rotating machinery and the floating platforms as a navigation hazard. Typically the surface water pump installation will need to be cordoned off with a line of buoys.

Lighted buoys at intervals along the line should be installed to warn boaters at night. The buoy line will also limit access to the area immediately surrounding the pumps. Nevertheless, further precautions must be taken to avoid injury to those that disregard the buoy line. Warning signs should be easily visible on the pumps ("HIGH VOLTAGE", "ROTATING MACHINERY"). Cable reels can apply tension to the power supply cables to keep them out of the water. A protective enclosure is desirable around the impeller to prevent injury to swimmers. The installation at Douglas Dam included a wire cage made of fencing that extends from the platform to a depth 2-feet below the impeller.

Possible Modes of Failure. The most likely problems with operation of a surface water pump system are related to the connection and positioning mechanisms. The pounding of wind and boat generated waves can cause severe loadings to the stifflegs, hinged connections, and the connection to the dam. Failure can be avoided by careful design, a good maintenance program, and frequent inspection.

It is also necessary to inspect the area directly surrounding the pumps for the accumulation of debris. It is conceivable that reservoir debris could reduce the output of the pumps, or even damage the equipment.

Risk Analysis. In general, the working principles of using a surface water pump system for improving the DO content of lakes, rivers, and tailraces are well documented (Ref. 6-23, 6-25, and 6-26). Pumps have been installed successfully at a number of test sites with various conditions. The risks of installing a system are predominantly a result of site-specific problems and requirements. For example, over-penetration could be more detrimental at some sites than others depending on the type of sedimentation and the sensitivity of the tailrace. Or, the epilimnetic DO content may decrease at some sites to a level low enough to render the surface water pumps ineffective.

Sizing. The sizing of a surface water pump system is based on the required dilution. The improvement of the release can be predicted in terms of dilution using the following equation:

$$DO_{total} \times Q_{total} = DO_{hyp} \times Q_{hyp} + DO_{epi} \times Q_{epi}$$

where:

DO = dissolved oxygen content
Q = flowrate

and the subscripts "total", "hyp", and "epi" refer to the total flowrate, the hypolimnion and the epilimnion, respectively. Therefore, the required epilimnetic flow can be estimated using the desired DO content of the release and the average DO content of both the hypolimnion and the epilimnion:

$$Q_{epi} = Q_{total} * (DO_{total} - DO_{hyp}) / (DO_{epi} - DO_{hyp})$$

The limit of this equation is the epilimnetic flowrate equal to the total flowrate when the DO required equals the epilimnetic DO content. Note that this equation will provide a value for the epilimnetic flowrate actually withdrawn. Small losses will also occur which require the actual pumped flowrate to be sightly larger.

The dilution formula can also be used to predict the temperature of the release.

$$T_{tot} \times Q_{tot} = T_{hyp} \times Q_{hyp} + T_{epi} \times Q_{epi}$$

The calculated epilimnetic flowrate alone is not sufficient for designing a surface water pump installation. A minimum initial velocity is required for the surface water plume to penetrate to the required depth. A reasonable estimate for the velocity required in stratified reservoirs can be obtained using a method developed by Holland (Ref. 6-35). Holland represents the stratified[4] reservoir by two layers of different densities. The upper layer has the characteristics of the epilimnion. The sharp interface between the two layers is defined as the thermocline. The lower layer has the

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[4]Note that the equations presented pertain to a stratified reservoir. To design a system for a non-stratified reservoir that is experiencing deficient DO levels, the simplest approach is to assume conditions of a typically stratified reservoir are present, design the system, and include a variable speed control for the pump motor.

characteristics of the hypolimnion at the depth of the withdrawal zone. Holland developed the following equations for the penetration depth as a function of the densimetric Froude number:

$$\frac{Z}{D} = 1.66 \times Fr - 0.66 \qquad \text{for } Fr > 1.65$$

$$\frac{Z}{D} = 1.60 \times Fr \qquad \text{for } Fr < 1.65$$

where:

Z = the distance from the thermocline to the withdrawal zone
D = diameter of the pump plume at the thermocline
Fr = densimetric Froude number:

$$Fr = \frac{V}{\sqrt{\left(\frac{(p_{hyp} - p_{epi})}{p_{epi}}\right) \times g \times D}}$$

V = jet velocity at thermocline
p_{epi} = density of the epilimnion
p_{hyp} = density of the hypolimnion
g = acceleration of gravity (32.2 ft/sec^2)

From these equations, the required velocity can be defined as:

$$V = \left(\frac{1}{1.66}\right)\left(\frac{Z}{D} + 0.66\right)\sqrt{\left(\frac{p_{hyp} - p_{epi}}{p_{epi}}\right) \times g \times D}$$

for Fr > 1.65, and,

$$V = \left(\frac{Z}{1.66 \times D}\right) \sqrt{\left(\frac{p_{hyp} - p_{epi}}{p_{epi}}\right) \times g \times D}$$

for Fr < 1.65.

These equations can be used to evaluate the initial output velocity of fairly large diameter, low velocity pumps, because the entrainment and reduction in velocity as the plume travels from the propeller to the thermocline is small. Therefore, the initial output velocity can be used for "V" and the diameter of the pump propeller can be used for "D". If a small, high velocity pump is desired, the entrainment of the high velocity jet will have to be considered in order to specify a velocity and flowrate. This is described in detail by Holland.

The following steps are recommended to size a surface water pump system for a particular hydro project:

1. Gather data on the project including:

   - epilimnion DO content, temperature, density
   - release DO content, temperature, density
   - total release flowrate
   - depth from maximum pool to intake
   - desired release DO content
   - depth from minimum pool to intake

   All of these parameters should be evaluated for worst-case conditions, (i.e. full pool and strong stratification).

2. Evaluate the surface water flowrate required using the dilution equation described earlier. A reasonable number of pumps of a particular diameter can be assumed at this point to provide the surface water flowrate. The assumed velocity, a, for these pumps can be found using:

   $$V_a = Q_{epi} / (N * A)$$

   where:

   N = number of pumps
   A = swept area of pump

3. The estimated Froude number is calculated using the assumed velocity. The assumed diameter can now be used in the equations by Holland to find the required output velocity.

4. The output velocity and the assumed velocity must be compared to verify the validity of the assumptions. If the two values do not match, a new diameter can be chosen to increase or decrease the assumed velocity. This process can be repeated until the two values agree within about 10%.

5. At this point, the required epilimnetic flowrate, output velocity, number of pumps, and pump diameter have been evaluated. The power required for such a system is dependent on the parameters evaluated above and the efficiency of the impeller and drive. The efficiencies of commercially available impellers and drives, however, vary widely. The best way to estimate the power requirements is to approach a mixer manufacturer with the flowrate, diameter, and velocity, and let them propose a suitable piece of equipment. A rough estimate of the power required can be found using:

$$P = \frac{W}{t} = \frac{(0.5\ m\ V_0^2 - 0.5\ m\ V_i^2)}{t} = \frac{Q\ \rho\ V_0^2}{2\ g}$$

where:

P	= power in ft-lb/sec (1 hp = 550 ft-lb/sec)
W	= work
t	= time
m	= mass
Q	= pumped flowrate
ρ	= specific weight of surface water
g	= acceleration of gravity
V_i	= velocity of pump input (assumed to be zero)
V_o	= velocity of pump output

The actual power requirements will be 2- to 6-times this calculated value depending on the efficiency of the equipment.

Note that the velocities calculated using this method will be somewhat high for reservoirs that do not form a sharp thermocline, or for conditions other than maximum stratification.

7. If an unreasonable flowrate is required, ($Q_{epi} > 0.75\ Q_{tot}$) the surface water pump system could be sized to provide a base DO improvement in combination with a topping off system.

Working Example:

The following example will demonstrate a surface water pump sizing calculation for a hypothetical hydroelectric project. The characteristics of the project are:

Q_{tot} = total release flow = 5,000 CFS
L = depth of intake centerline at full pool = 100 ft
DO_{epi} = DO content of the epilimnion = 9.5 mg/L
T_{epi} = temperature of the epilimnion = 80.0 °F
p_{epi} = density of the epilimnion = 62.21 lb/ft^3
DO_{hyp} = DO content of the hypolimnion = 2.0 mg/L
T_{hyp} = temperature of the hypolimnion = 65.0 °F
p_{hyp} = density of the hypolimnion = 62.33 lb/ft^3
H = depth to thermocline = 20 ft
Z = L - H = distance from thermocline to intake = 80 ft
DO_{tot} = desired release DO = 5.0 mg/L
D = pump diameter (feet)

The required epilimnetic flow would be:

$$Q_{epi} = Q_{total} * (DO_{total} - DO_{hyp}) / (DO_{epi} - DO_{hyp})$$

$$Q_{epi} = 5{,}000 \text{ CFS} * (5 - 2) / (9.5 - 2) = 2{,}000 \text{ CFS}$$

This is a substantial amount of water to be moved, about 40% of the total release flowrate. The temperature increase due to the operation of the pumps would be about 6°F.

An initial guess of four pumps, 15-feet in diameter, each moving 500 CFS, results in a velocity (V) of 2.8 ft/s. The Froude number for this initial guess would be:

$$Fr = \frac{2.8}{\sqrt{\left(\frac{(62.33 - 62.21)}{62.21}\right) \times 32.2 \times 15}} = 2.9$$

using:

$$V = \left(\frac{1}{1.66}\right)\left(\frac{Z}{D} + 0.66\right)\sqrt{\left(\frac{p_{hyp} - p_{epi}}{p_{epi}}\right) \times g \times D}$$

$$V = \left(\frac{1}{1.66}\right)\left(\frac{80}{15} + 0.66\right)\sqrt{\left(\frac{62.33 - 62.21}{62.21}\right) \times 32.2 \times 15} = 3.49 \frac{ft}{sec}$$

This value is higher than the first guess, so the process is repeated with D = 14-feet and V_{guess} = 3.25 ft/s:

$$Fr = 3.73$$
$$V = 3.46 \text{ ft/s}$$

This value is within 10% of the assumed velocity and can therefore be used for sizing the pump system.

The power required for driving one pump can be estimated:

$$P = \frac{Q \rho V^2}{2 g}$$

$$= 500 \text{ CFS} * 62.2 \text{ lb/ft}^3 * (3.25 \text{ ft/sec})^2 / (2 * 32.2 \text{ ft/sec}^2)$$
$$= 5{,}100 \text{ ft-lb/sec}$$
$$= 9.3\text{-hp}$$

Using an average pump efficiency of 25%, P_{final} = 37-hp or about 40-hp. Therefore, this system would require four, 40-hp pumps moving 500 CFS each at about 3.25 ft/s.

Costs. The costs associated with building permanent surface water pump systems will be a function of the size and output velocity required for each pump. These costs are not well defined because all of the systems installed at hydro powerplants have been experimental in nature. For the planned permanent installation at TVA's Douglas Dam, vendors of mixing equipment were contacted to supply the motor, drive and impeller. The reported costs for the installation of three (3) 30-hp, 15-ft diameter pumps, discharging at 3.0 ft/s are as follows:

Description	Material	Labor	Total
Motors, drives, & impellers	$210,000		$210,000
Floating platforms	$30,000		$30,000
Engineering Design & Supervision		$30,000	$30,000
Assembly		$15,000	$15,000
Transportation	$5,000	$5,000	$10,000
Stiff leg system	$5,000	$5,000	$10,000
Electrical supply	$24,000	$12,000	$36,000
Variable speed drives	$15,000	$1,000	$16,000
Installation		$20,000	$20,000
Safety Equipment	$15,000	$10,000	$25,000
Biofouling chemical system	$2,000	$2,000	$4,000
TOTAL	$306,000	$100,000	$406,000

These costs are budget estimates that will vary with the size and power requirements of the pumps as well as difficulty of installation. The life expectancy of this system would be about 10 years. Operating costs for the pumps would include electric power consumed and maintenance.

For a quick estimate of the cost of an epilimnion surface water pump application, TVA uses an overall figure of $4,000/hp (1988 dollars).

Case Histories. Two major variations of surface water pumps have been tested. One using a large diameter, low speed, axial flow propeller; the other using a small diameter, high speed axial flow propeller. Professor James Garton originally investigated the suitability of large diameter axial flow pumps for improving the water quality of reservoir releases (Ref. 6-27 and 6-28). He installed and tested pumps ranging from 3.5-feet in diameter to 17-feet in diameter at various lakes in the mid-west (Ref. 6-29 and 6-30).

Three pumps were assembled and tested by Professor Garton with the cooperation of Union Electric Company at Bagnell Dam on the Lake of the Ozarks in Missouri during August 1982 (Ref. 6-31). The velocity

of the discharge of the pumps was approximately 2.5 ft/s for a total discharge of 1,320 CFS. During testing, these pumps were successful at increasing the 4,080 CFS discharge by better than 2 mg/L (from 1.3 to 3.6 mg/L). The use of the pumps was discontinued, however, due to maintenance problems with the connection pieces between the flotation platforms.

TVA acquired these pumps from Union Electric in 1986. A revised flotation platform and connection design was used for their installation at TVA's Douglas Dam (Ref. 6-32), where they have been tested extensively in various spacing and location arrangements (Ref. 6-33).

The first arrangement was a triangle formation as shown in Figure 6-17 (essentially the same as at Bagnell Dam). This formation was tested at several distances from the intakes. The intake trashracks at Douglas extend upstream of the face of the dam in a half-cylinder with a radius of 25-feet. The most effective distance seemed to be about 10-feet between the intake trashrack and the nearest edge of the impeller. This allowed the increasing diameter of the pump plume (due to entrainment and movement toward the intake) to develop without being deflected by the solid cap of the intake structure[5]. These pumps were operated an average of seven hours a day during two months of the summer of 1987 with no operational problems. The pumps were quiet and required minimal maintenance. They were successful in improving the DO content of the 4,000 CFS discharge from Unit 4 by about 1 mg/L (from near 0.0 to 1.0 mg/L) during strong stratification conditions. The number of hydroturbine units in operation at the dam increased the withdrawal zone of Unit 4 vertically and nearly doubled the effectiveness of the pumps as shown in Figure 6-18.

A further arrangement was tested that separated the pumps by one impeller diameter. This arrangement (Figure 6-19) was installed in 1988 with the pumps in an arc around the intake structure. This

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[5]In 1987 the pumps were rearranged into a straight line parallel, then perpendicular to the dam. The spacing between the impellers was 3 feet for both cases. No significant changes in performance were observed. In all cases where the impellers were located near each other, the effectiveness of the three pumps did not equal the sum of the effects due to each pump operated individually.

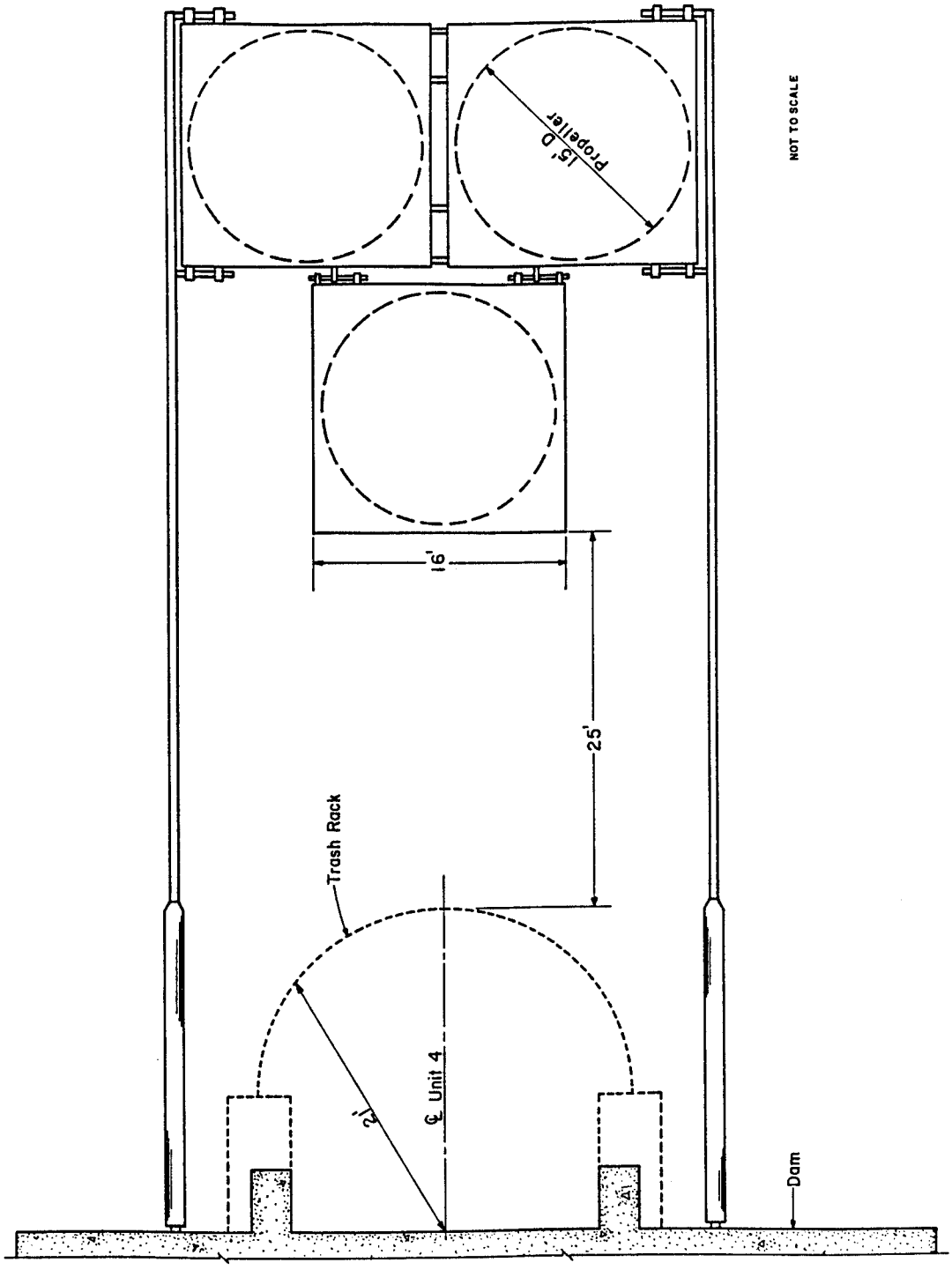


Figure 6-17. Surface Water Pumps at Douglas - 1st Arrangement.

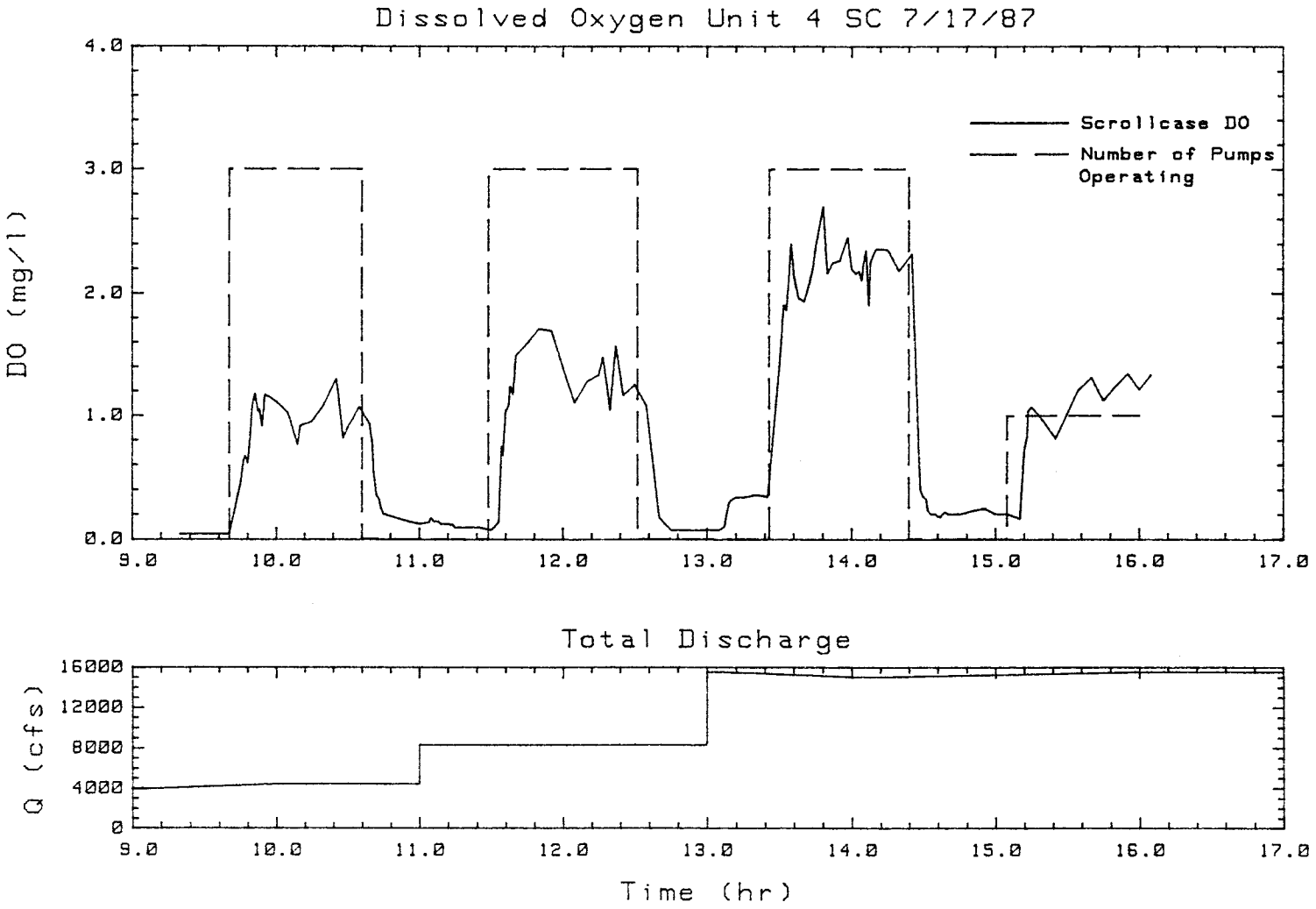


Figure 6-18. Doubling Effectiveness of Surface Water Pumps, Aarrangement 1.

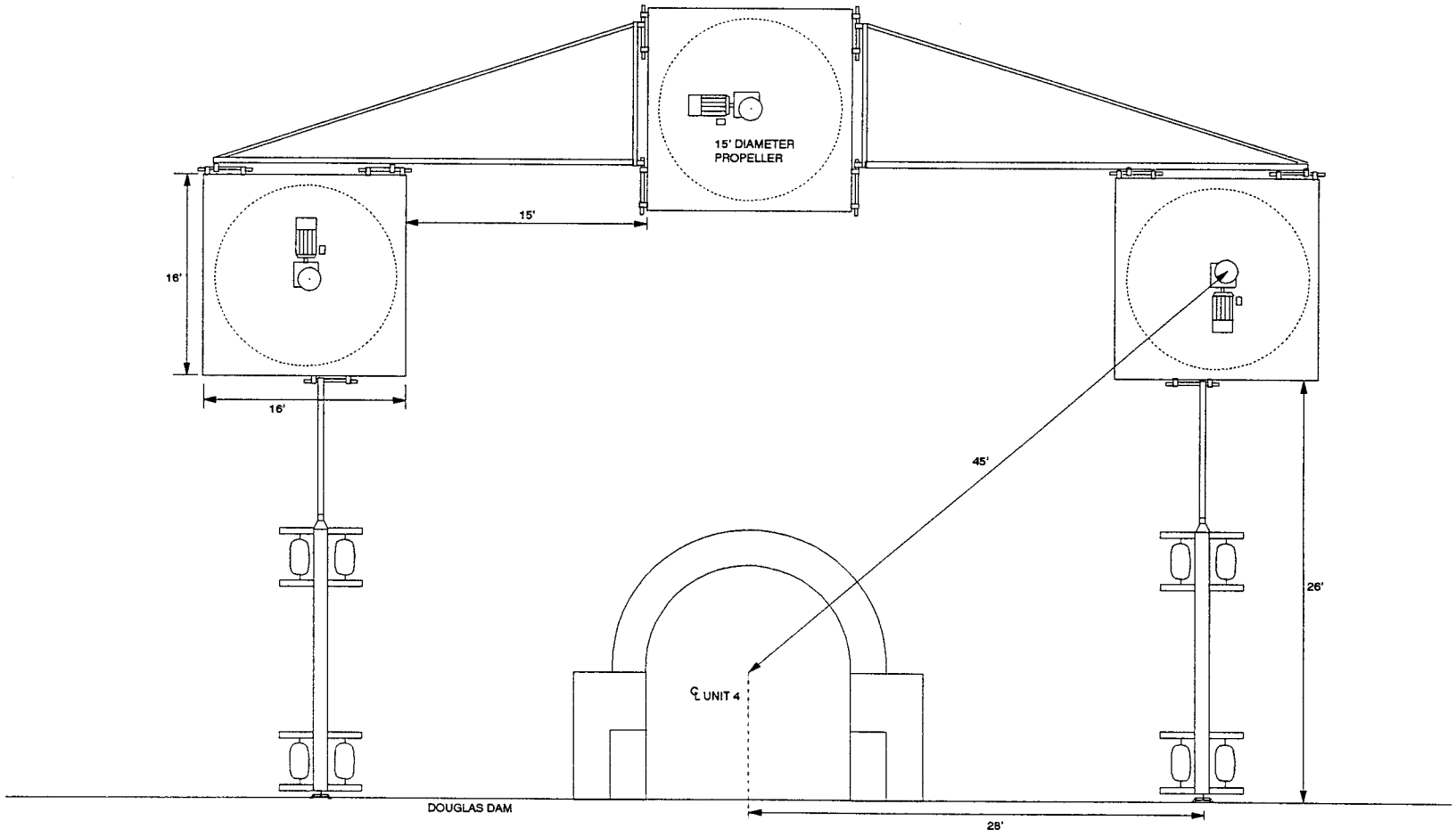


Figure 6-19. Surface Water Pumps at Douglas - 2nd Arrangement.

arrangement yielded much better results. Using three 30-hp pumps, DO content of the 4,000 CFS release from Unit 4 improved by 2 mg/L (0.1 to 2.1 mg/L) under strong stratification conditions as shown in Figure 6-20. However, the total effect of the simultaneous operation of all three pumps was still not equal to the sum of the pumps when operated individually. Operation of the pumps caused an average temperature increase of about 1 degree Centigrade in the tailrace, depending on reservoir conditions. Wind and wave loading of the sliding connection on the face of the dam proved to be a major problem. The mechanism was replaced with larger rail and a rolling connection shown in Figure 6-21 that has proven mostly trouble free.

An unexpected problem which developed late in the summer of 1987 was clogging of the coolers of Unit 4 due to biological growth and siltation. The cooling water for the stator cooling air and the thrust bearing oil is taken from the unit penstock. The cooling water flow became restricted due to biological growth and siltation in the cooler tubes. The increased biological activity was blamed on the increased DO content of the water flowing through the coolers. The siltation that built up was attributed to the stirring of siltation by the over-penetration of the surface water pumps while operating during periods of weak stratification. A chemical additive system was installed at Douglas at a cost of about $4,000 to alleviate the problem. This system was operated satisfactorily during 1988 but low water conditions and the installation of other equipment have prevented extensive testing.

A small diameter surface water pump system has been tested by the United States Army Corps of Engineers (COE) during 1987 at J. Percy Priest Dam near Nashville, TN (Ref. 6-34). These pumps consisted of a 1.6-ft (0.5-m) diameter impeller driven at 900 RPM by a 40-hp electric motor as shown in Figure 6-22. Three pumps discharged about 45 CFS each at an average velocity of 21.9 ft/s. The pumps were simple and relatively inexpensive ($25,000) since the impeller is direct drive. These pumps are easy to launch from a boat ramp and trailer because the small impeller is located near the bottom of the float. The design of the small diameter pumps relies on the tremendous entrainment of the high velocity, small diameter jet to build up a significant pump output (Ref. 6-35). For these pumps, the epilim-

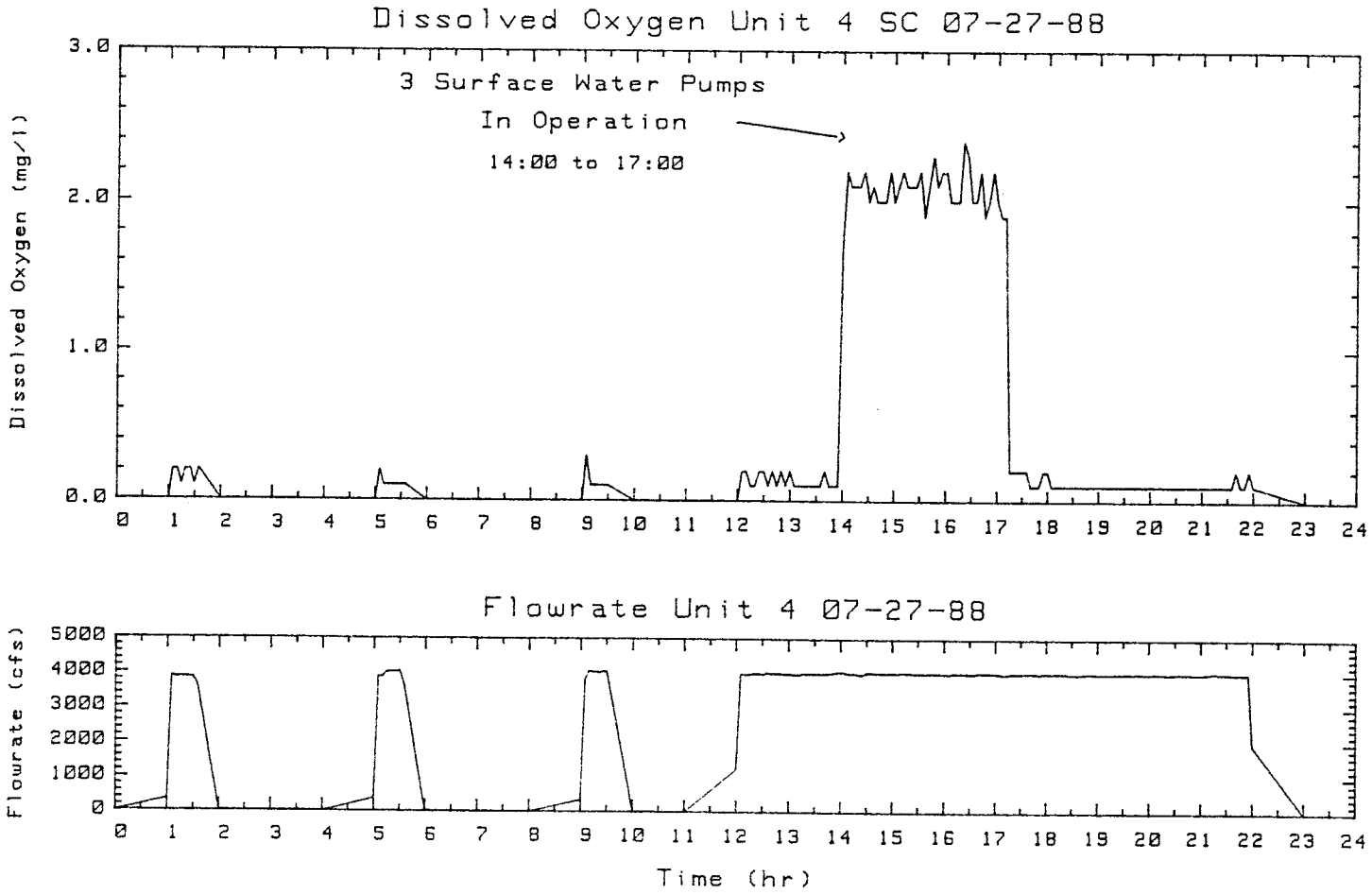


Figure 6-20. Effectiveness of Surface Water Pumps at Douglas, Arrangement 2.

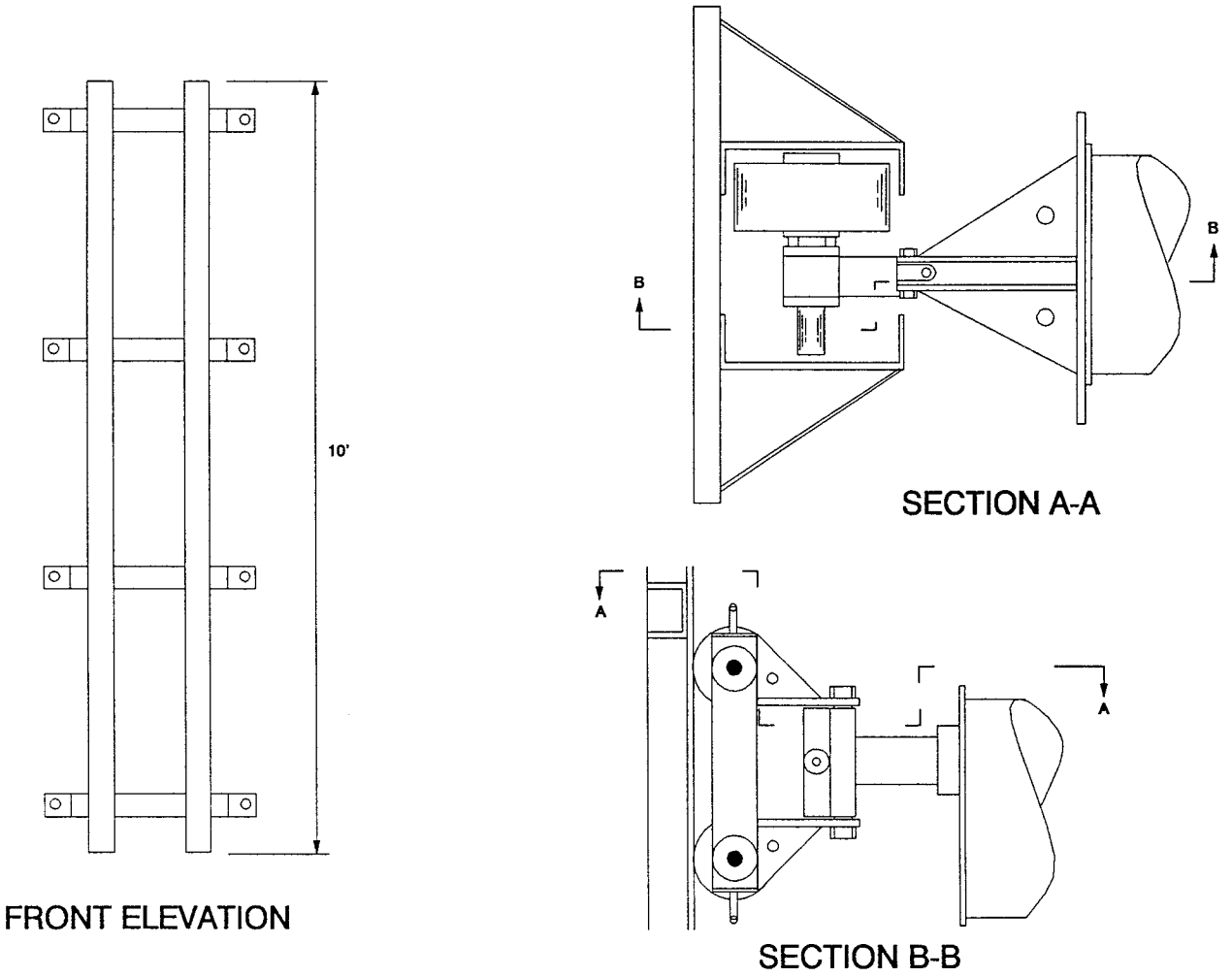


Figure 6-21. Surface Water Pump Connection to Dam.

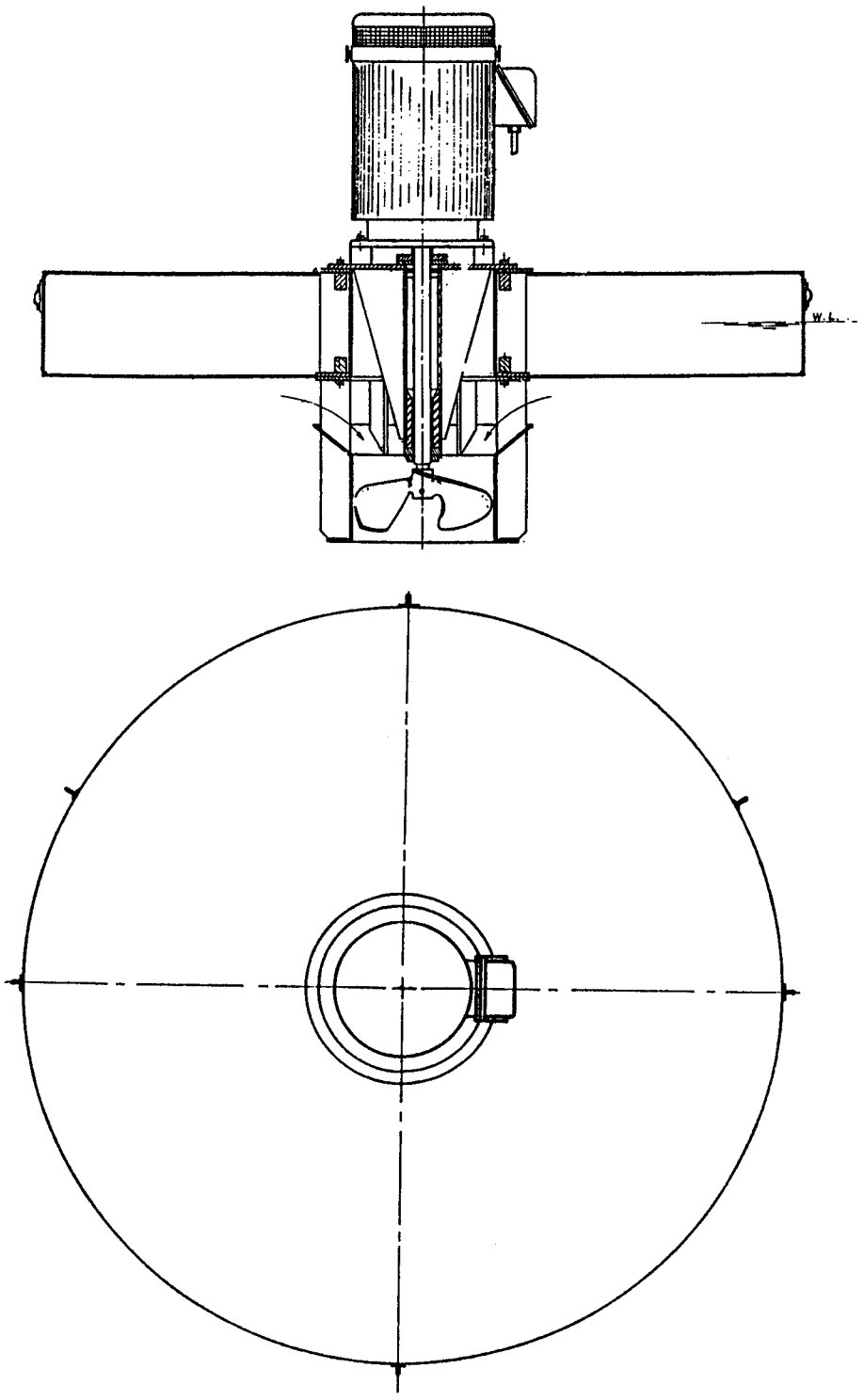


Figure 6-22. Schematic Drawing of Direct Drive Mixer (Reproduced With Permission of Aeration Industries International, Inc.).

netic flow is measured at the thermocline or the bottom of the high DO content water. The pumps were consistently able to increase the DO content of the 4,600 CFS release at J. Percy Priest by 1.0 to 1.3 mg/L (from 2.7 to 4.0 mg/L). The pumps were less effective per horsepower than the large diameter pumps, but were less expensive and easier to install.

Potential Suppliers of Surface Water Pump Equipment.

Burhans-Sharpe Co.
2255 Harbor Ave S. W.
PO Box 3906
Seattle, WA 98124
(206) 932-1030

Lightnin Mixing Equipment Co
135 Mt Read Blvd.
PO Box 1370
Rochester, NY 14603
(716) 436-5550

ProQuip Inc.
850 East Highland Rd.
Macedonia, OH 44056-0165
(216) 468-1850

Gas Injection, Forebay

Physical Aspects. Although other forms of aeration techniques such as surface aerators or weirs may be more applicable to smaller discharges and deficits, when the flows increase to several thousand CFS, or the deficit reaches 4 mg/L or more, or energy revenues are of high priority, oxygen injection techniques should be considered. Because gas transfer efficiency is enhanced under pressure, the upstream reservoir is preferred for gas injection. Additionally, because the intake withdrawal zone is a known and predictable area, and the required facilities for gas injection are more available, experimental aeration techniques have concentrated in the area near the intake.

Due to the likelihood of inducing supersaturation with dissolved nitrogen gas and the significant increase in the required number of diffusers if air were injected, these systems are nearly always restricted to pure oxygen injection.

Forebay gas injection systems installed to date have consisted of fine bubble diffuser located within the withdrawal zone of the intake, supplied with pure oxygen (Ref. 6-36, 6-37, 6-38, and 6-16), as illustrated in Figure 6-23. Other possible approaches include downflow bubble contactors and devices used to aerate the reservoir's hypolimnion.

Working Principles. The placement of the diffusers in the forebay is meant to take advantage of the depth (high pressures) to increase oxygen transfer and the local currents to aerate only the water passing through the turbine. Two important site-specific design parameters are reservoir depth for the diffusers and the depth of the penstock intake. Given sufficient reservoir depth, transfer efficiency can reach 100%. However, if the withdrawal zone in a stratified reservoir is totally within the hypolimnion, the bubbles may rise above the withdrawal zone before absorption occurs.

Limitations, Constraints, and Trade-Offs. If absorption time is not sufficient, oxygen bubbles may pass directly into the intake and discharged via the draft tube, without being absorbed. These bubbles may cause reduced turbine efficiency and possibly increased corrosion. Therefore, limitations exist as to the proper depth of the diffusers and the proper location to maximize withdrawal of treated water.

Because the systems are located in close proximity to the powerhouse, they effectively use the intake withdrawal zone to minimize the amount of oxygen injected, and little, if any, of the reservoir is used for storage of aerated water prior to its passage downstream. Usually, the system must be capable of instantaneously treating the maximum hydraulic capacity of the facility at the greatest DO deficit. Aeration systems located further upstream in the reservoir (see Reservoir Techniques) take advantage of the lag time between aeration and actual passage of the water through the turbine, and require smaller investments of initial capital and equipment.

Major Obstacles To Installation. As with all diffuser systems in the reservoir, the depth is a benefit for oxygen transfer, but a hindrance during installation. The racks of diffusers must be submerged

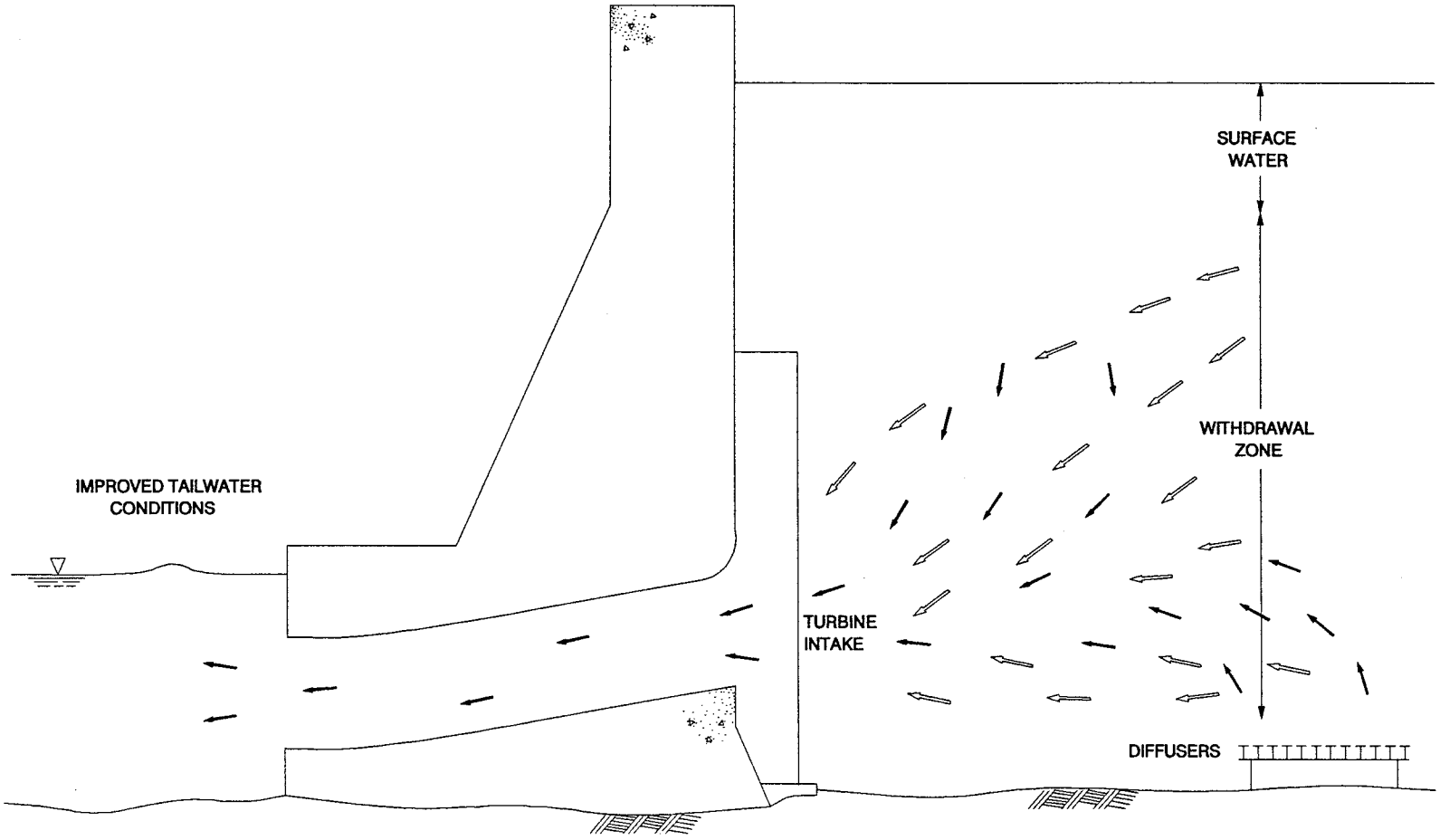


Figure 6-23. Typical Forebay Gas Injection Technique.

near the dam and anchored in place. If the bottom is not flat, or it is littered with submerged debris, installation is more difficult. Uneven terrain on the reservoir floor can be corrected with adjustable supports on the diffuser racks.

Environmental Effects. Adverse environmental effects are limited to the source of oxygen for the diffusers. If a LOX system is replaced with an on-site generation plant, both visual and audible environmental effects must be considered. Because the diffuser system is located on the bottom of the reservoir, it has very little negative impact environmentally, but many positive effects on the water quality of the entire reservoir.

Equipment Life Expectancy. In the harsh environment of waste treatment applications, flexible membrane diffusers last 2- to 6-years. For reservoir applications operated approximately 6-months of the year, the diffusers should last 10-years or more, when membrane replacement will become necessary. The distribution piping system, if properly designed and constructed, will last considerably longer than the diffusers. A 30-year life can be expected based upon limited applications of this type.

If a LOX system is used to supply oxygen, it is recommended that equipment be leased from the supplier, thereby relieving the owner of the responsibility of maintenance. If an on-site oxygen generation plant (see Appendix G) is part of the design, equipment life will depend upon the annual number of hours of operation and the maintenance provided. The critical components of these systems are the compressors. With good maintenance, air compressors should last the life of the system (30-years) (Ref. Ingersoll Rand).

Safety. In addition to the safety items associated with pure oxygen as discussed in Appendix G, the hazards of installing and maintaining systems submerged at depths of 100-feet or more should be considered. Experienced divers, however, are trained to work at these depths, and should be familiar with the proper safety precautions that must be taken.

Modes of Failure. Modes of failure can include an interruption of the oxygen supply to the system, a rupture of an oxygen supply line, or diffusers clogged with biological or chemical matter. If the system is located too close to the intake, adequate contact time may not exist for efficient absorption, and bubbles may enter the penstock. The bubbles would result in reduced turbine efficiency and possibly additional corrosion of equipment. If the system is poorly designed, the flow rate to diffusers and/or the number of diffusers may not be adequate to meet the oxygen deficit.

Risk Analysis. Although several modes of failure can occur, the technique of oxygen injection near the powerhouse is known to have been successfully tested at four facilities in the U.S. (Douglas Dam, Richard B. Russell, Patrick Henry Dam, Clark's Hill). Owners using data and experiences gained through these tests can minimize the risk for their applications. Additionally, the system has an inherent flexibility that allows it to be expanded or relocated at relatively minor expense.

Sizing.

Working Example:

Assumptions:

Discharge flow:	2,700 CFS
Minimum powerhouse DO discharge:	0.0 mg/L
Discharge DO requirement:	5.0 mg/L
Reservoir depth near dam:	100-feet
Depth to hypolimnion:	30-feet

Oxygen requirement:

A maximum of 5.0 mg/L must be transferred at a flow of 2,700 CFS. The maximum oxygen demand is:

$$2{,}700 \text{ CFS} * 28.32 \text{ L/ft}^3 * 5 \text{ mg/L} * 60 \text{ sec/min} = 50.5 \text{ lbs/min}$$

To determine the size of the diffuser array, a transfer efficiency (oxygen absorbed/oxygen injected) must be assumed for the site-specific conditions. Transfer efficiencies for similar installations and various oxygenation tests (Ref. 6-39, 6-16, and 6-40) generally

range from 60% to 95%, depending upon the specific circumstances, and how "transfer efficiency" was defined in each case. For this example, a conservative transfer efficiency of 75% has been selected, keeping in mind that if the technique appears favorable, the calculations should be repeated using a range of efficiencies (i.e., original assumed transfer efficiency +/- 10%).

If the injection system is assumed 75% efficient, 67.4 lbs/min would be required to be injected when both the maximum discharge and the maximum deficit occur simultaneously. At 70°F and 1-atmosphere pressure, oxygen weighs 0.08279 lbs/ft^3. Thus, to inject 67.4 lbs/min would require:

$$67.4 \text{ lbs/min} * (1/0.08279) \text{ ft}^3/\text{lb} = 814 \text{ CFM}$$

If 13-inch flexible membrane diffusers are used (see section 6.1 Tailwater Techniques, Tailrace Gas Injection/Submerged Diffusers, Working Example) at a loading rate of 6.6 SCFM per diffuser, 124 diffusers would be required. Using a mounting design similar to the one at Douglas Dam (Figure 6-9 and Figure 6-10), two racks would be required, each measuring approximately 16-feet by 35-feet.

For this example, the oxygen would be supplied from a LOX system leased from a local oxygen supplier. The LOX system would require storage tanks and vaporizers, and must be located to allow access by delivery trucks. The actual size of the storage facility would best be determined by the LOX vendor, provided
he has information concerning maximum oxygen demand and a general idea of the back-up storage desired. Generally, a 2-day reserve of oxygen is sufficient.

Referring to Appendix G, if the LOX system supplies oxygen at 100 PSIG and a 10 PSI frictional pressure loss is experienced in a supply line 800-feet long, a 3-inch diameter supply pipe would be required. The supply pipe would be joined to each of the diffuser arrays via a flexible hose. Copper piping is standard for oxygen systems.

If the oxygen injection system appears to be a viable alternative, comparisons between LOX, pressure-swing absorption (PSA) systems, and cryogenic supply systems should be made. An example of this type of comparison can be found in Appendix G.

Cost: Costs for the above example will include design, installation, and annual operation and maintenance. Equipment costs can be divided into the diffuser system and the LOX equipment. An estimate of the unit price for the diffuser hardware would be $100/each (1989 dollars), including the diffuser, distribution piping, and the anchoring/support system. Total equipment cost for the diffuser system: 124 * $100 = $12,400. Installation labor is considerably higher than similar systems in tailwater applications because of the need for deep-water divers. The price of installing each diffuser is estimated to be $130 each, for a total of $16,120. The installation of the main supply header and site work for the leased LOX equipment for this example is approximately $20,000.

Summary of installation costs:

Diffuser system hardware:	$12,400
Diffuser system labor:	16,120
LOX site work/supply line install.:	20,000
Subtotal:	$48,520
Engineering (10%):	4,852
Total:	$53,372

To determine the annual costs, it will be assumed that the system operates 5-months of the year, the facility generates 6-hours per day, and the average oxygen deficit per month will be:

Month 1:	2 mg/L
Month 2:	4 mg/L
Month 3:	5 mg/L
Month 4:	5 mg/L
Month 5:	4 mg/L

Annual operating costs must include labor, maintenance, oxygen, and miscellaneous items such as insurance. If the life of the system is assumed to be 30-years, insurance is estimated as 1/30th the install-

ation cost, less engineering fees. Operational labor will consist of turning the system on at the beginning of plant generation, making periodic adjustments to the oxygen flow rate during generation, and shutting the system down when generation ceases. Assuming the controls are manual and located remote to the powerhouse, this effort could require up to 3-man-hours during each generating period, or approximately 450-man-hours per year. At a cost of $30.00 per hour, operational labor would be $13,500 annually.

Annual maintenance of the system will be minimal, particularly since the LOX system is leased. Maintenance items can consist of repairs required to the supply pipe or individual hoses to the diffuser racks. An annual maintenance budget of $5,000 should suffice.

The cost to lease LOX equipment will depend upon the vendor and the volume of oxygen, and local price conditions. Local suppliers are the best source of cost estimates for particular sites, but for a typical hydro-application, a monthly lease rate of $1,300 would include storage tanks, vaporizers, and regulators. The cost of leasing is bore year-round, irregardless of whether the oxygen system is in use or not.

The above oxygen demand and operational schedule can be used to determine the approximate volume of oxygen injected yearly. If 67.4 lbs/min of oxygen are required when the deficit is 5 mg/L, the monthly oxygen requirement would be:

Month 1:	146 tons
Month 2:	291 tons
Month 3:	364 tons
Month 4:	364 tons
Month 5:	291 tons
Total:	1,456 tons

If the cost of oxygen is $75.00 per ton, the annual expenditure would be (1,456 * $75.00) = $109,200.

Operation of the system only requires pressure, which is supplied by the LOX system via the vaporization process, and oxygen injection will not affect turbine efficiency unless the diffuser arrays are

install improperly and quantities of undissolved oxygen reach the turbine machinery. Thus, there are no annual energy or replacement generation costs.

The total annual operating costs would be:

Insurance (1/30th of initial cost):	$1,617
Purchase of oxygen:	109,200
Lease of LOX equipment:	15,600
Labor:	13,500
Total:	$139,917

The Present Worth of a 30-year series of an annual costs of $139,917 at 12% interest is $1,127,031.

If the life of the diffusers is assumed to be ten years, and the installed replacement cost is $130.00 each, an expenditure of $16,120 would be required at the end of 10- and 20-years.

Thus, the total Present Worth of injecting pure oxygen into the forebay is:

Initial installation:	$53,372
Present Worth, annual operations:	1,127,031
Present Worth, membrane replacement, 1st ten years:	5,191
Present Worth, membrane replacement, 2nd ten years:	1,672
Total:	$1,187,266

($147,387 per annum for 30-years at 12%)

Case History. Since 1988, TVA has been testing the use of pure oxygen via flexible membrane diffusers located near the trashracks at Douglas Dam. The diffusers are designed to augment an existing epilimnion surface water pumping system by providing and additional 2 mg/L of DO in the facility's discharge. The results presented here were achieved without the surface pumps operating.

The system consisted of three racks, each having seventy-eight 9-inch diameter flexible membrane diffusers. The racks were evaluated in two different configurations, both at a depth of approximately 140-feet, and aerating a flow of 4,000 CFS. The first configuration

located the racks in an arc around the intake, with a radius of approximately 100-feet (Figure 6-24, Scheme 1). Testing at various supply rates resulted in overall downstream absorption efficiencies of 30% to 55% (Figure 6-25). Efficiency was calculated by measuring the actual increase of the DO in the tailwater compared to the amount of DO injected through the diffusers located in the forebay[6]. As such, the efficiency does not reflect the total amount of oxygen absorbed by the water because it does not include the oxygenated water that remained in the reservoir.

The second configuration placed the racks tightly around the intake (Figure 6-24, Scheme 2). With flow rates as high as 5.5 CFM per 9-inch diameter diffuser, the overall oxygen transfer efficiency ranged from 72% to 76% (Ref. 6-16) (Figure 6-26). TVA attributes the increase in efficiency to the fact that rising bubbles were being swept into the penstock, rather than escaping the withdrawal zone and rising to the surface, as was the case in the first configuration.

Testing was planned to continue through 1989, with additional, larger racks of diffusers installed to serve the other generating units at the facility.

Gas Injection/Turbine

The water passageways both upstream and downstream from a turbine provide locations of confined flow where air or oxygen can be conveniently introduced. Gas injection in these passageways is not an uncommon practice. Air to reduce vibrations and cavitation has been successfully introduced upstream from the turbine in the spiral casing, in the annular space between guide wheel and runner, and in the disc friction zones around the runner (Ref. 6-41). Downstream from the runner, air has been introduced through the runner cone, at the cavitation ring and through the cross bracing sometimes present in the draft tube. Air or oxygen for the purpose of increasing DO in

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[6]This definition of efficiency should not be confused with the transfer efficiency as used in other examples in this manual, although it is similar. Other sections use transfer efficiency in the context of the total amount of oxygen absorbed by the water versus the total amount injected. In this example, not all the absorbed oxygen will be passed downstream.

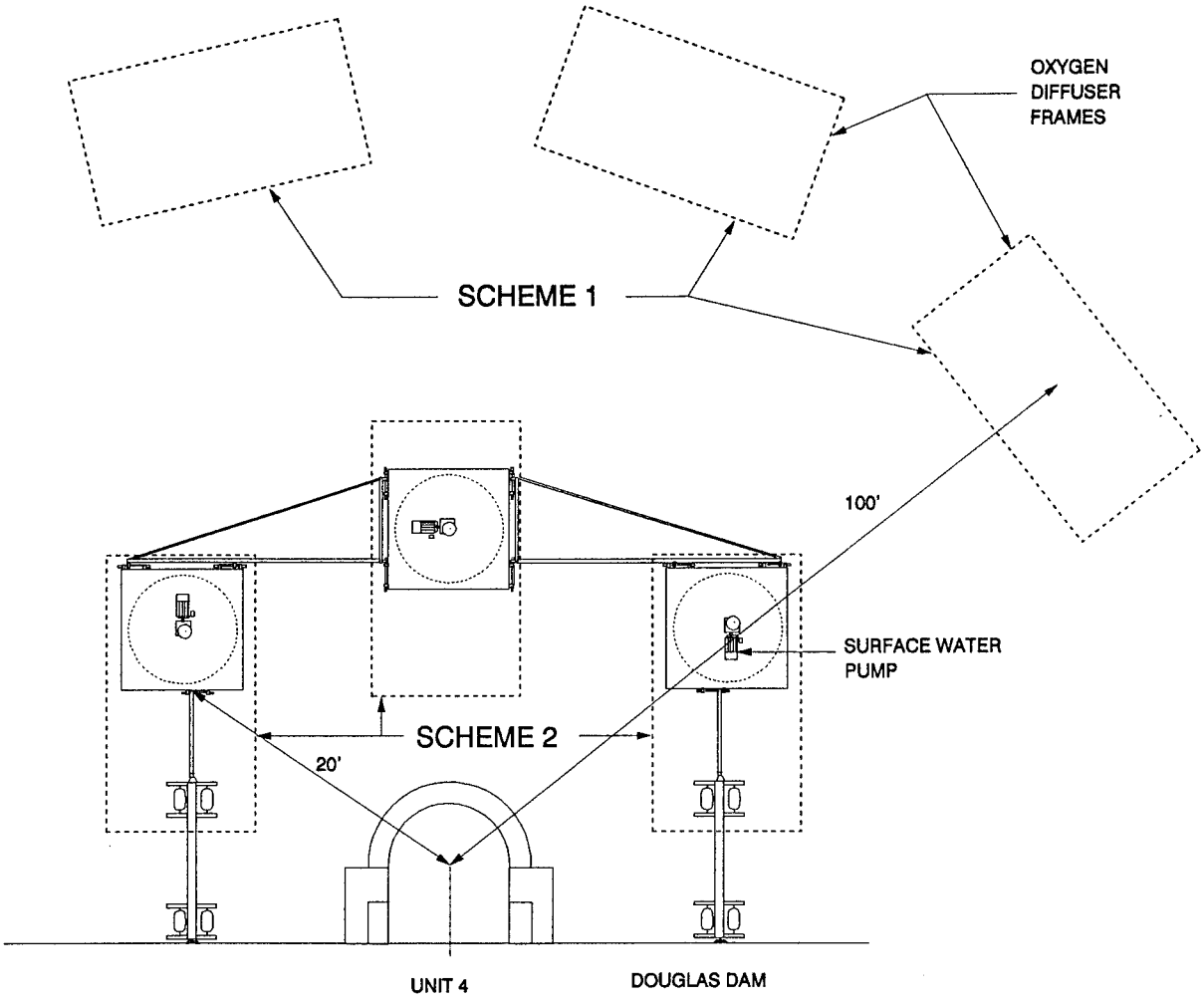


Figure 6-24. Configuration of Diffusers 2 schemes at Douglas Dam.

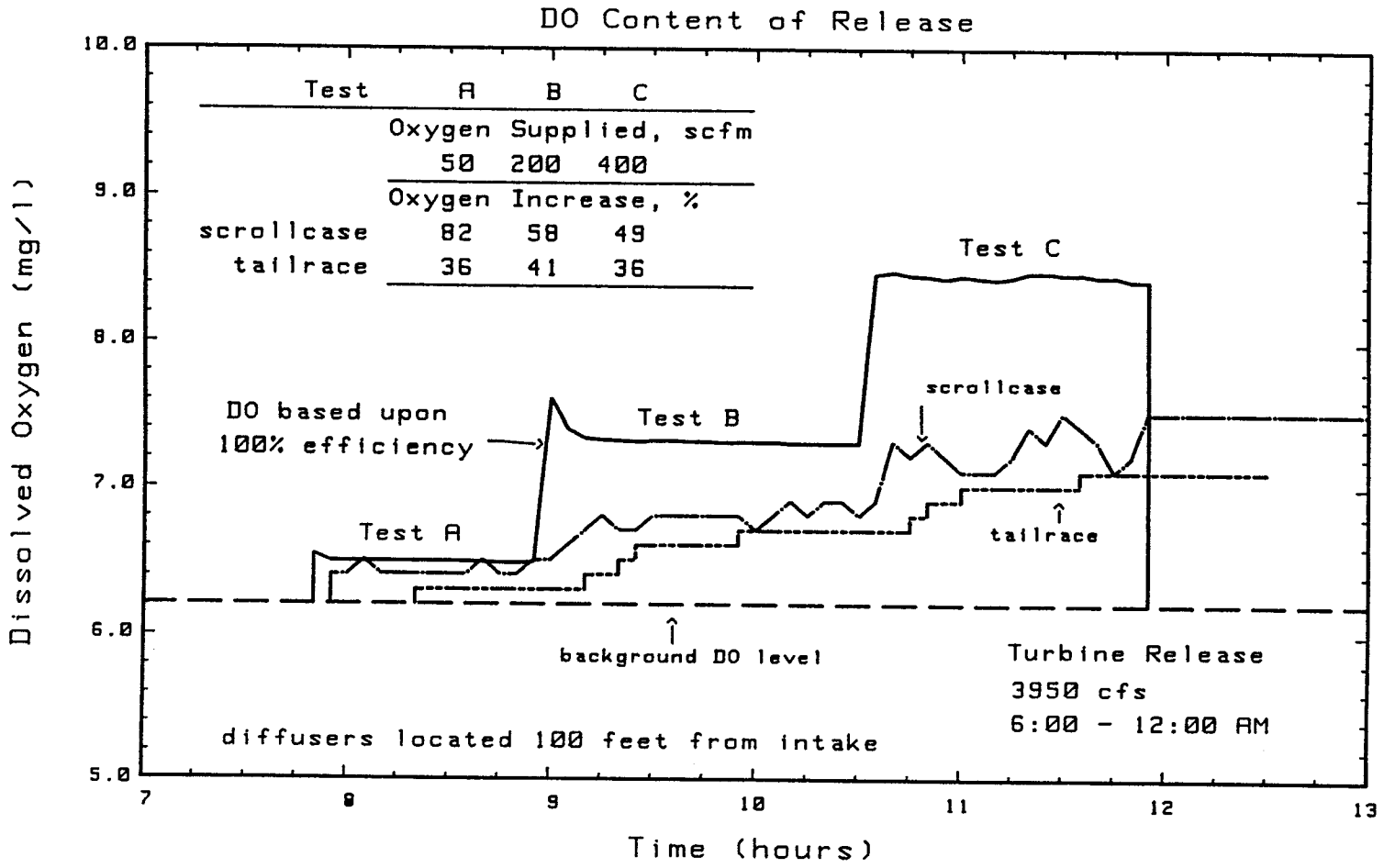


Figure 6-25. Effectiveness of Oxygen Diffusers at Douglas, Scheme 1.

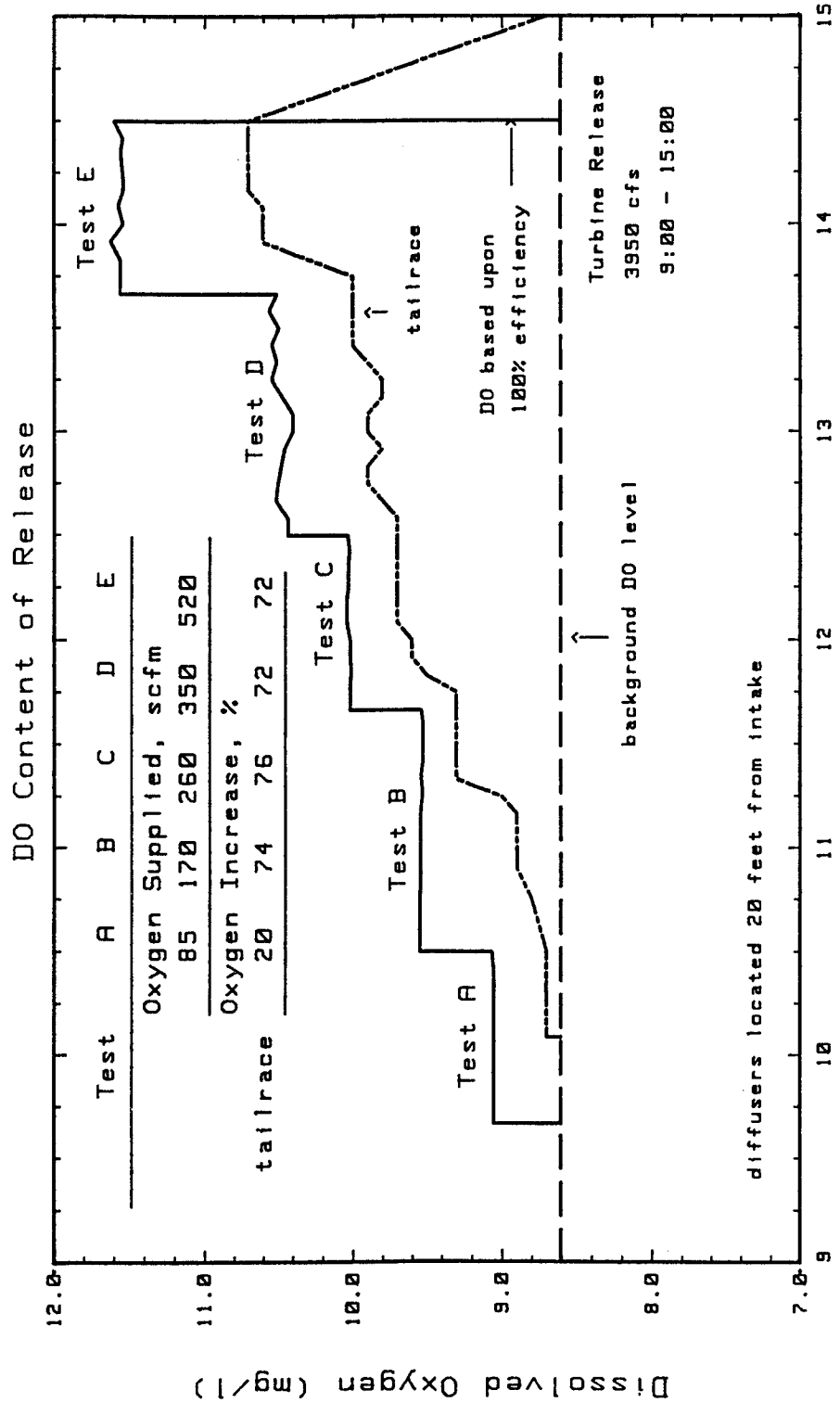


Figure 6-26. Effectiveness of Oxygen Diffuser at Douglas, Scheme 2.

the discharges can also be added in these passageways. However, the quantities of air necessary to significantly increase DO are usually much greater than the quantities necessary for vibration and cavitation control. In very general terms, field tests have indicated that the percentage of air by volume introduced into the turbine flow increases DO on a one-to-one basis (i.e., one percent air gives 1 mg/L DO, 2 percent gives 2 mg/L, etc). No data is available for air percentages greater than about 5%.

There are three potential locations for injecting air or oxygen for aeration within the powerhouse: upstream of the turbine (penstock), at the turbine, and downstream of the turbine (draft tube). Injecting large quantities of gas immediately upstream of turbine machinery to counter large DO deficits (i.e., 4 mg/L) causes obvious problems. The large deficit requires a considerable portion of the flow to be comprised of air. This not only reduces the energy available for power generation, but also may cause the turbine to operate in a very unpredictable and possibly dangerous manner. Pure oxygen could be substituted for air, reducing the quantity of injected gas by a factor of 5, but the use of pure oxygen within the powerhouse raises many safety concerns. The injection of gas upstream of the turbine, and the injection of pure oxygen from locations within the powerhouse have not been extensively researched and applied, and will not be considered in this manual.

The latter two categories of gas injection, however, have been tested more extensively. Downstream turbine methods usually involve the introduction of air slightly below the runner, through the draft tube wall. This approach has been substantially developed by Alabama Power Company. Methods of injection at the turbine itself generally involve retrofitting the vacuum breaker system, and have been investigated by TVA. Self-venting turbines, which by design will induce air, are currently under study by TVA with the intent of constructing and testing several prototypes. This method holds promise for significant improvements at sites where runner replacements can be justified.

Draft Tube Venting Systems

Physical Aspects. When compared to turbine injection, draft tube systems are more difficult and expensive to install in an existing facility, but are more predictable. As illustrated in Figure 6-27, draft tube venting systems utilize several injection ports located immediately downstream of the turbine, where maximum use can be made of the relatively low ambient pressures. To enhance the aspiration, deflector plates are also usually mounted on the draft tube wall, perpendicular to the streamflow, and just upstream of the ports.

Although compressors have been used to provide additional air to the draft tube, their use is generally only considered when the draft tube pressure is too high to aspirate the required volume of air. Compressors can be used to overcome piping losses, but may also inject so much air as to greatly impede turbine operations. If space is available, the piping of a naturally vented system can be sized large enough to minimize friction losses and provide sufficient air at the point of injection to meet the DO objective.

Working Principles. Draft tube injection takes advantage of the highly turbulent waters and the hydrostatic pressures encountered just below the runner to enhance oxygen transfer. Transfer efficiency is highly site-specific, and depends on a number of variables, including oxygen deficit, number of injection ports, deflector plate alignment, draft tube configuration, unit loading, hydrostatic pressure below the runner, number of units operating, type of turbine, water/gas contact time, tailwater depth, and tailrace configuration. Turbine efficiency is decreased by gas injection, even though the point of injection is slightly downstream of the machinery. This decrease must be accounted for in the economic analysis of this technique.

Limitations, Constraints, Trade-offs. The major limitation of draft tube air injection is the overall amount of oxygen uptake that can occur. The uptake is dictated by the conditions occurring at the site, such as draft tube pressures and water/air contact time, and is further limited by the amount of air that can be injected without

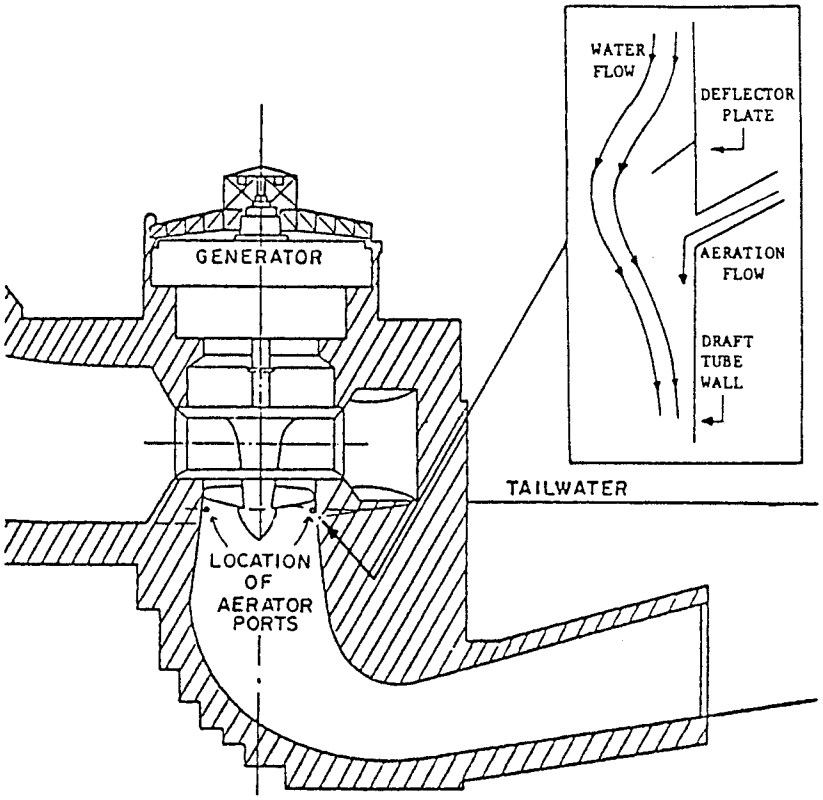


Figure 6-27. Draft Tube Turbine Venting (Ref. 6-42)

drastically affecting turbine performance. Currently, the practical limit of air flow is approximately 4% of the water flow.

In actual field installations, DO uptake has varied over a range of less than 1 mg/L to greater than 4 mg/L, with 2 mg/L being most typical. The greater increases were accomplished by reducing the unit load to lower the pressure directly below the runner.

The biggest trade-offs associated with draft tube venting systems are related to energy production. Venting has resulted in a reduction of generator output that has ranged from less than 1% to more than 5%. Typically, a loss of approximately 2% can be expected. The loss also manifests itself in Replacement Generation Capacity which should be included in the overall economic analysis.

Draft tube venting is not the most flexible of the aeration alternatives. Although it is theoretically possible to throttle the volume of air entering the unit, the systems are normally opened to atmosphere and allowed to operate without supervision. Thus, whenever deflector plates are present and/or air is introduced into the turbine flow, an efficiency loss is likely to occur.

One factor that affects oxygen uptake in all aeration systems is bubble size. With current draft tube systems, bubble size is not a controllable parameter. The air usually enters the draft tube through pipes 2- to 6-inches in diameter. To inject finer bubbles, pipe size would have to be reduced with a corresponding increase in the number of pipes.

Major Obstacles to Installation. Draft tube venting systems require piping access to the area just below the runner. At existing facilities, this has been accomplished by routing large diameter vent piping from the exterior of the powerhouse, through the spiral case, and then boring holes through the concrete to the draft tube. Because numerous holes must be bored and the vent pipe must be routed through an existing concrete structure, installation can become a major obstacle.

Environmental Effects. Negative environmental effects associated with draft tube venting systems are few. If compressors and/or pure oxygen equipment are part of the design, noise can become a problem, along with visual impact.

Equipment Life Expectancy. Because there are no moving parts involved with naturally vented draft tube aeration systems, the life expectancy would have to be as long as the structure it serves. The equipment consists of steel pipe and standard valves, the maintenance of which is very straightforward.

Safety. Due to the static nature of the technique, few safety hazards exist. If the deflector plates are removed at the end of the aeration season (thereby eliminating a source of turbine energy loss), normal safety precautions must be observed when working below the runner.

In the rare instance when compressors are involved to enhance the amount of air injected, typical "moving machinery" hazards exist, along with heat generated by compression. If pure oxygen is used, extra care must be taken not to introduce flammable materials and sources of ignition.

Possible Modes of Failure. The foremost mode of possible failure with draft tube aeration systems is the inability of the installation to meet the designers' expectations. In spite of the fact that the technique has worked at other locations, the methods of predicting system performance have not advanced to the point of being 100% dependable. Numerous interrelated variables may act in unpredictable ways, resulting in disappointing performance. Additionally, because draft tube venting can only be reasonably expected to provide an approximate DO increase of up to 3 mg/L, should local conditions deteriorate more than expected, venting may not meet the standard.

Other than a poor system design and/or a drastic reduction in reservoir DO levels, few modes of failure exist for naturally vented draft tube aeration systems. Operators may fail to open the vent valve, not allowing atmospheric air to be drawn into the system. If the

deflector plates are not fastened well, they may break loose, reducing aeration efficiency.

If compressors are incorporated into the design, the chances of failure increase due to the machinery. Good maintenance procedures will lessen the chance of mechanical failure. Typical risks with oxygen systems include a stoppage of delivery from commercial vendors or a breakdown with on-site generation equipment.

Risk Analysis. Because the methods of predicting oxygen uptake are not 100% reliable, and the fact that preliminary testing of the technique is not easily accomplished, the risk for this approach is slightly higher when compared to diffuser systems, particularly for cases with large DO deficits. However, if the deficit is in the 1- to 2 mg/L range, risk is reduced considerably. Several draft tube aeration systems have been installed and considerable data is available concerning design, installation, and operation. This will certainly help to reduce risk.

Sizing. Basic empirical equations used to size draft tube aeration systems have been developed by Alabama Power Company, and have been described through a number of publications (Ref. 6-17, 6-42 and 6-43)[7]. The procedure is summarized as follows:

1. Determine the maximum DO deficit that can occur in the turbine discharges.

2. Calculate the maximum air flow (4% of water flow).

3. By incrementally applying the equations developed by the Alabama Power Company (below) along the length of the draft tube and tailrace, estimate the increase in both dissolved oxygen and nitrogen.

4. If the estimated increase in dissolved oxygen will meet the discharge standard and the water will not become supersaturated with dissolved nitrogen, use basic engineering hydraulics (Bernoulli's equation) to estimate the pressure at the point of injection. If the pressure is less than atmospheric, draft tube venting is feasible. If the pressure is slightly greater than atmospheric, the effect of deflector plates must be closely scrutinized to determine

[7]Wilhelms, et al. (Ref. 6-91), also presented a similar approach.

if they artificially provide a pressure less than atmospheric at the point of injection.

5. Estimate the annual cost of lost power revenues assuming a 2% reduction in generator output whenever the venting system is operational.

6. Design deflector plate/port configuration and aeration piping layout, incorporating birdscreen, noise suppression device, and safety valving. Minimize pressure losses by selecting large-diameter pipe sizes. Estimate the cost of installation, including any lost power revenues that may be incurred due to the construction.

7. If the economics indicate that draft tube venting is the best alternative compared to other options, install the equipment.

The maximum DO deficit is obtained from the facility's water quality monitoring data and the imposed water quality standards. The equations developed by Alabama Power Company to estimate dissolved oxygen and dissolved nitrogen increases are:

$$\Delta DO = \alpha \ (Q_a/Q_w) \ (C_s - C) \ (1.024)^{T-20} \ \Delta t$$

where:

ΔDO	=	Dissolved oxygen uptake (mg/L)
α	=	Draft tube coefficient[8] (sec^{-1})
Q_a	=	Air flow (CFS)
Q_w	=	Water flow (CFS)
C_s	=	Oxygen saturation concentration (mg/L)
C	=	Oxygen concentration (mg/L)
T	=	Temperature (°C)
Δt	=	Contact time (seconds)

and:

$$\Delta DN = 0.93 \ \alpha \ (Q_a/Q_w) \ (C_{sn} - C_n) \ (1.024)^{T-20} \ \Delta t$$

[8]The engineers at Alabama Power have empirically derived α to be 0.6830 sec^{-1} (Ref. 6-17).

where:

ΔDO = Dissolved oxygen uptake (mg/L)
α = Draft tube coefficient (sec^{-1})
Q_a = Air flow (CFS)
Q_w = Water flow (CFS)
C_{sn} = Nitrogen saturation concentration (mg/L)
C_n = Nitrogen concentration (mg/L)
T = Temperature (°C)
Δt = Contact time (seconds)

Initial dissolved nitrogen levels can be measured using a dissolved oxygen meter and a saturometer (Ref. 6-44). Table 6-5 illustrates Alabama Power's accuracy of predicting DO levels using this approach, compared to measured values at three aeration sites.

Table 6-5

PREDICTED/MEASURED VALUES DISSOLVED OXYGEN AND NITROGEN CONCENTRATIONS

Facility	Q_{AIR}/Q_{WATER}	Dissolved Oxygen Predicted/Measured	Dissolved Nitrogen Predicted/Measured
Logan Martin	0.0053	5.71 / 5.73 mg/L	13.65 / 13.60 mg/L
Martin	0.0411	4.17 / 4.11	16.64 / 16.30
Holt	0.0026	4.78 / 4.65	14.80 / 14.80

Source: Alabama Power Company (Adapted from Ref. 6-43)

Working Example:

Assumed conditions:

Maximum hydraulic flow:	1,350 CFS
Minimum incoming powerhouse DO level:	0.0 mg/L
Powerhouse dissolved nitrogen discharge:	14.8 mg/L
Discharge DO requirement:	3 mg/L
Water temperature:	12°C
Elevation of tailwater (operating):	874.5 feet
Elevation of bottom of runner:	873.5 feet
Generator output at normal gate opening:	11.25 MW
Term of operating license:	30-years

With a discharge requirement of 3 mg/L and a minimum incoming DO level of 0.0 mg/L, the maximum deficit is 3.0 mg/L. Based upon successful, previous installations, the maximum air flow is 4% of the water flow, or 54 CFS. The oxygen saturation level of water at 12°C is 10.77 mg/L (Appendix G). Because the saturation level of a dissolved gas is depth dependent, the equations developed by Alabama Power must be applied incrementally as the water passes through the draft tube and on into the tailwater. Normally, the relationship of pressure-versus-time in the draft tube is modeled and input along with basic background information (i.e. initial dissolved oxygen, dissolved nitrogen, temperature values) is fed into a computer program. The program calculates the DO and DN levels for every 0.1 second as the water passes through the draft tube, using the levels calculated for the n-th location to serve as input for the n+1 location. To demonstrate the process and estimate the DO and DN uptake, the working example will only examine four discreet increments, taken at locations approximately 1.5 seconds apart as the water travels through the draft tube. Table 6-6 presents the necessary site-specific data to perform the calculations.

Table 6-6

DRAFT TUBE VENTING EXAMPLE: SITE-SPECIFIC DATA
(Locations are approximately 1.5 seconds apart)

Location	Time (sec)	Centerline Elevation (feet)	Draft Tube Area (sq. ft.)	Velocity (ft/sec)	Distance Traveled (feet)
1	0.0	871.00	56.75 ft^2	23.8	0
2	1.5	854.50	144.0	9.4	25
3	3.0	855.75	204.0	6.6	37
4	4.5	856.50	240.0	5.6	44

(Location #1 is at the point of injection.)

Bernoulli's Equation is used to calculate the pressures at each location:

$$P_N = [(H_{tw} - H_N) - (V_N^2/2g) + h_N] * (\gamma/144)$$

where:

P_N = Pressure at Location N
H_{tw} = Tailwater elevation when generating
H_N = Elevation of Location N
V_N = Velocity in draft tube (ft/second)
g = Acceleration of gravity (32.2 ft/sec^2)
h_N = Frictional loss in draft tube to Location N (Normally estimated as a head loss of 1-foot over the full length of draft tube.)
γ = Density of water (62.4 pounds/ft^3)

Knowing the pressure at each location, an equivalent depth, Z, can be calculated (a column of water 1-meter in depth exerts 1.42 PSI). Appendix G provides the saturation concentrations of oxygen and nitrogen at sea-level and 12°C (10.77 mg/L and 17.39 mg/L, respectively), and the relationship to determine the actual saturation concentration prevailing at each location. For example, the pressure at Location 2 is:

$$P_2 = [(H_{tw} - H_2) - (V_2^2/2g) + h_2] * (\gamma/144)$$

$$= [(874.5 - 854.5) - (9.4^2/64.4) + (25/44)] * (62.4/144)$$

$$= 8.32 \text{ PSIG}$$

The equivalent depth at Location 2 is:

$$Z = 8.32/1.42 = 5.86 \text{ meters}$$

The dissolved oxygen and nitrogen saturation concentrations are:

$$C_{SAT-DO-2} = 10.77 \left(1 + \frac{5.86}{10.35}\right) = 16.87 \text{ mg/L}$$

$$C_{SAT-DN-2} = 17.39 \left(1 + \frac{5.86}{10.35}\right) = 27.24 \text{ mg/L}$$

The results of the calculations for all levels are summarized in Table 6-7.

Table 6-7

SUMMARY OF PRESSURE/SATURATION CONCENTRATION CALCULATIONS

Location	Pressure (PSIG)	Equivalent Depth (meters)	Saturation Concentration Oxygen (mg/L)	Nitrogen (mg/L)
1	-2.29	-1.61	9.09	14.68
2	8.32	5.86	16.87	27.24
3	8.20	5.77	16.77	27.08
4	8.02	5.65	16.65	26.88

Table 6-7 indicates that the pressure at the point of injection (Location 1) is negative, making natural venting possible. It also illustrates the large effect that depth has on saturation concentration, and hence, the driving force behind gas transfer.

The equations to determine ΔDO and ΔDN can now be used to calculate the gas uptake between the locations. The DO uptake that occurs between Location 1 and Location 2 is:

$$\Delta DO_{1-2} = (0.683)(0.04)\left[\frac{(9.09 + 16.87)}{2} - 0.0\right]1.024^{(12-24)}(1.5)$$

$$= 0.44 \text{ mg/L}$$

Because the initial DO level at Location 1 was 0.0 mg/L, the DO level at Location 2 is 0.0 + 0.44 = 0.44 mg/L. It should be noted that the saturation concentration was the average value of that calculated for Location 1 and Location 2.

Next, the ΔDO is calculated between Locations 2 and 3:

$$\Delta DO_{2-3} = (0.683)(0.04)\left[\frac{(16.87 + 16.77)}{2} - 0.44\right]1.024^{(12-24)}(1.5)$$

$$= 0.56 \text{ mg/L}$$

Thus, the DO level at Location 3 is 0.44 + 0.56 = 1.00 mg/L. In a similar manner:

$$\Delta DO_{3-4} = (0.683)(0.04)\left[\frac{(16.65 + 16.77)}{2} - 1.00\right]1.024^{(12-24)}(1.5)$$

$$= 0.53 \text{ mg/L}$$

The DO at Location 4 is 1.00 + 0.53 = 1.53 mg/L.

Aeration continues in the tailrace. Assuming a bubble-rise velocity of 3 feet/second, the Δt will be (874.5 - 856.5)/3.0 = 6.0 seconds. Applying the ΔDO equation for the final time:

$$\Delta DO_{TAILRACE} = (0.683)(0.04)[16.65 - 1.53]1.024^{(12-24)}(6.0)$$

$$= 2.05 \text{ mg/L}$$

The final DO level is calculated to be 1.53 + 2.05 = 3.58 mg/L. It must be reiterated that accuracy of the method would be improved if smaller time increments were used.

The same method is used to calculate ΔDN. The results are summarized in Table 6-8.

Table 6-8

SUMMARY OF PREDICTED DISSOLVED OXYGEN AND NITROGEN LEVELS

Location	ΔDO, mg/L	ΔDN, mg/L
1 - 2	0.44	0.19
2 - 3	0.56	0.38
3 - 4	0.53	0.37
4 - Tailrace	2.05	1.40
Final Levels:	3.58	17.14

The above method indicates that less than atmospheric pressure exists below the runner, and that a natural draft should occur, provided supply piping is properly sized to minimize frictional losses. The final DO level, with an initial DO level of 0.0 mg/L, is 3.58 mg/L. The final DN level of 17.14 mg/L is below saturation.

Costs. Because of the nature of the installation (large-diameter piping in confined spaces with concrete building construction), draft tube venting costs are very site-specific. However, the greatest portion of the expense of a draft tube venting system may not be due to installation, but rather to lost power revenues.

Power losses for installed systems have ranged from less than 1% to greater than 5%. For the working example, a typical loss of 2% will be assumed.

If the generators are normally operated 6-hours/day, and venting is required 5-months of the year, the 2% generation loss is annually valued at:

2% * 6 hrs/day * 150 days * 11,250 kW * $0.06/kWh = $12,150

For this case, a period of approximately 8-weeks will be required for installation, during which time no power will be generated. The value of the lost power revenues during this outage is[9]:

6 hrs/day * 56 days * 11,250 kW * $0.06/kWh = $226,800

Finally, the cost of actually installing the equipment for the system must be estimated. The components of a typical draft tube venting system are illustrated in Figure 6-28. The piping is relatively straightforward, except for the construction and installation of the distribution header. Each system should have a birdscreen, noise suppression device, gate valve, check valve, and a secondary (option-

[9]If the water remains in storage during the installation, the cost of Lost Power Revenues may not apply.

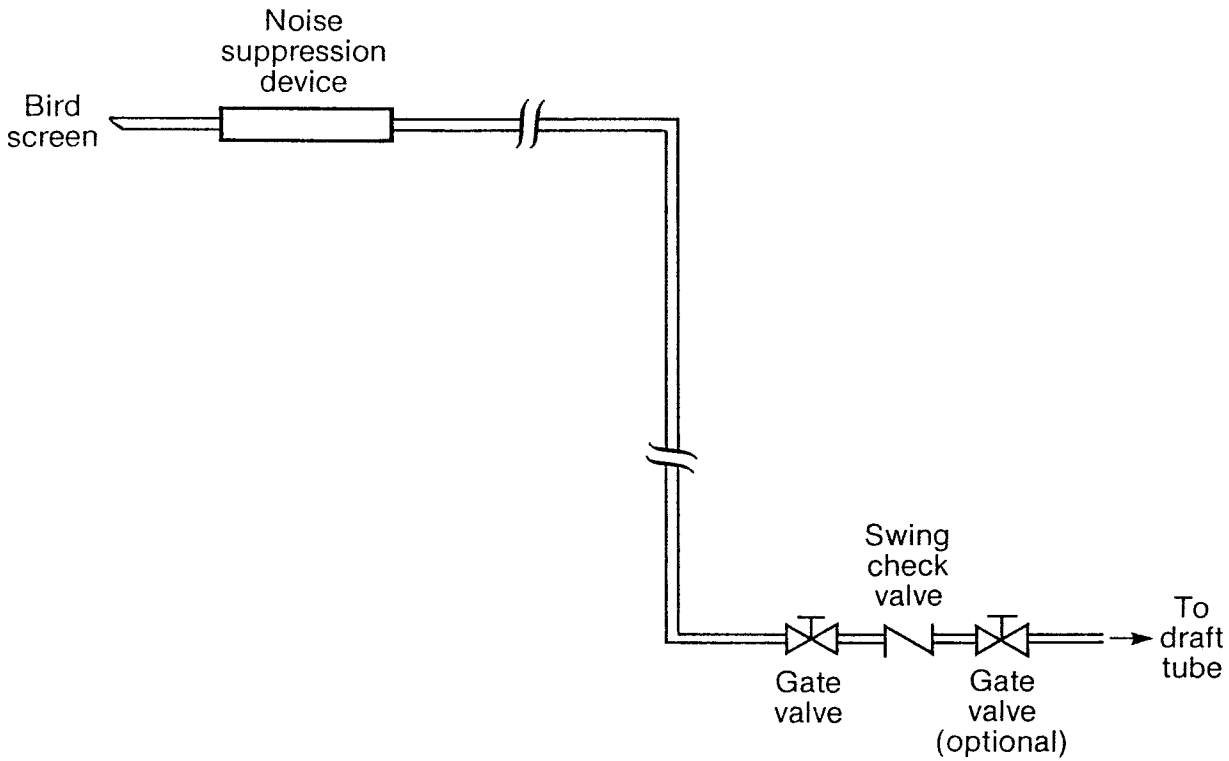


Figure 6-28. Typical piping components of a draft tube venting system.

al) gate valve to allow for servicing of the check valve. Since frictional pressure losses must be minimized, the design of the piping should be done by an experienced engineer. For the Working Example, the following list of installation costs was derived for the site-specific installation:

12-inch supply line, installed:	$3,800
12-inch elbows (4), installed:	2,120
12-inch tee (1), installed:	1,000
12-inch gate valve (1):	1,600
12-inch check valve (1):	1,700
12-inch silencer, installed:	1,700
Birdscreen, installed:	500
Reducers:	3,000
Fabrication of header:	10,000
Concrete drilling:	3,000
Baffles, installed:	4,000
Painting:	3,000
Subtotal:	$35,420
Engineering:	3,542
Total:	$38,962

Other minor annual costs will include a small amount of maintenance, and insurance (1/30th of original equipment cost).
The total annual costs are:

Lost power revenues:	$12,150
Insurance:	1,181
Maintenance:	1,000
Total:	$14,331

The Present Worth of a series of 30 annual payments of $14,331 each at 12% interest is $180,682.

The total Present Worth of the draft tube venting system is:

Initial installation:	$38,962
Lost power revenues during 8-week installation period:	266,800
Annual cost (Present Worth):	115,436
Replacement Generation Capacity:	
Total Present Worth:	$381,198

($47,324 per annum for 30-years at 12%)

Case Study. Alabama Power Company and Dr. Donald C. Raney (University of Alabama) performed the first dedicated research on draft tube aeration in the early 1970s. Alabama Power has installed and now operates deflector plate systems on thirteen hydroelectric turbines at six different projects. These installations include propeller and Francis type wheels, with flow rates ranging from about 3,000 CFS to over 10,000 CFS, and operating heads from 60-feet to 150-feet. Dissolved oxygen uptake capabilities range from about 0.5 mg/L to over 3.0 mg/L.

The earliest application occurred at Logan Martin Dam on the Coosa River. The powerhouse at Logan Martin houses three 43-MW generators using fixed-blade propellers. The hydraulic head is approximately 60-feet, and the water flow is 10,000 CFS per unit. The designers first began experimenting with turbine aeration by adapting the existing tailwater-depression piping of Unit #2 for air injection. The system consisted of a 10-inch diameter intake and a 6-inch diameter distribution manifold supplying four 6-inch diameter injection ports. Each port had a 30° baffle mounted upstream.

With an air flow of 60 CFS (0.6%), the incoming DO level of 5.0 mg/L was increased to 5.5 mg/L. With this early success, the company went on to install a total of 13 draft tube venting systems. The last retrofit occurred in 1986, again at Logan Martin Dam. This time Unit #2 received a completely new system. The main inlet is 18-inch diameter pipe, supplying a distribution manifold that gradually reduces in diameter. The manifold supplies a total of eight 6-inch diameter ports, each equipped with a 45° deflector plate. At the time, the cost of the installation was estimated at $250,000.

With an air flow of 400 CFS (4%) and an incoming DO level of approximately 4 mg/L, the system is capable of increasing the DO of the discharge by 2 mg/L. With the draft tube venting system operating, the best gate opening is altered, and the result is approximately a 5.5% reduction in power generation.

Vacuum Breaker Systems

Physical Aspects. Hydroturbines are typically equipped with vacuum breaker systems which function is to prevent sudden pressure changes from occurring should the water flow through the turbine stop abruptly. The vacuum breaker system usually consists of an air passage through the headcover with exit ports on the turbine hub. A cam operated, spring loaded valve opens or closes the air passage as necessary. It is often possible to aerate turbine flows via the vacuum breaker system by simply opening or removing the valve so that air can be induced. A schematic of a vacuum breaker aeration system is shown in Figure 6-29. In this system, the vacuum breaker valve has been bypassed and hub baffles over the ports have been added to increase suction.

As with draft tube venting systems, the amount of air that can be induced through the vacuum breaker depends upon the pressure at the exit ports and resistance in the air passages to the ports. On existing turbines, the pressures around the hub are very difficult to measure, can be predicted only by complicated calculations, and will change with unit loading. The best way to determine if vacuum breaker venting is a viable means of enhancing DO levels for an existing unit is to simply open the vacuum breaker valve during operation and measure the induced air flow. Using this airflow and the known geometry of the vacuum breaker piping, the pressure at the exit ports can be estimated. Knowing the pressure at the ports allows a larger, more efficient air supply system to be designed.

If insufficient suction pressures are present at the vacuum breaker exit ports, more suction can be created by installing small baffles over the ports on the hub, similar to the baffles used in draft tube venting. Unlike draft tube baffles, however, the performance of hub baffles are more difficult to predict because of the flow patterns acting around the hub.

An alternative to adding baffles is to force air into the water using blowers or compressors. Increasing the pressure under the crown of a turbine, however, can cause changes in loads and alignment which, although small, may significantly effect cavitation damage, bearing loads, and seals. Once the air has been injected into the water, the

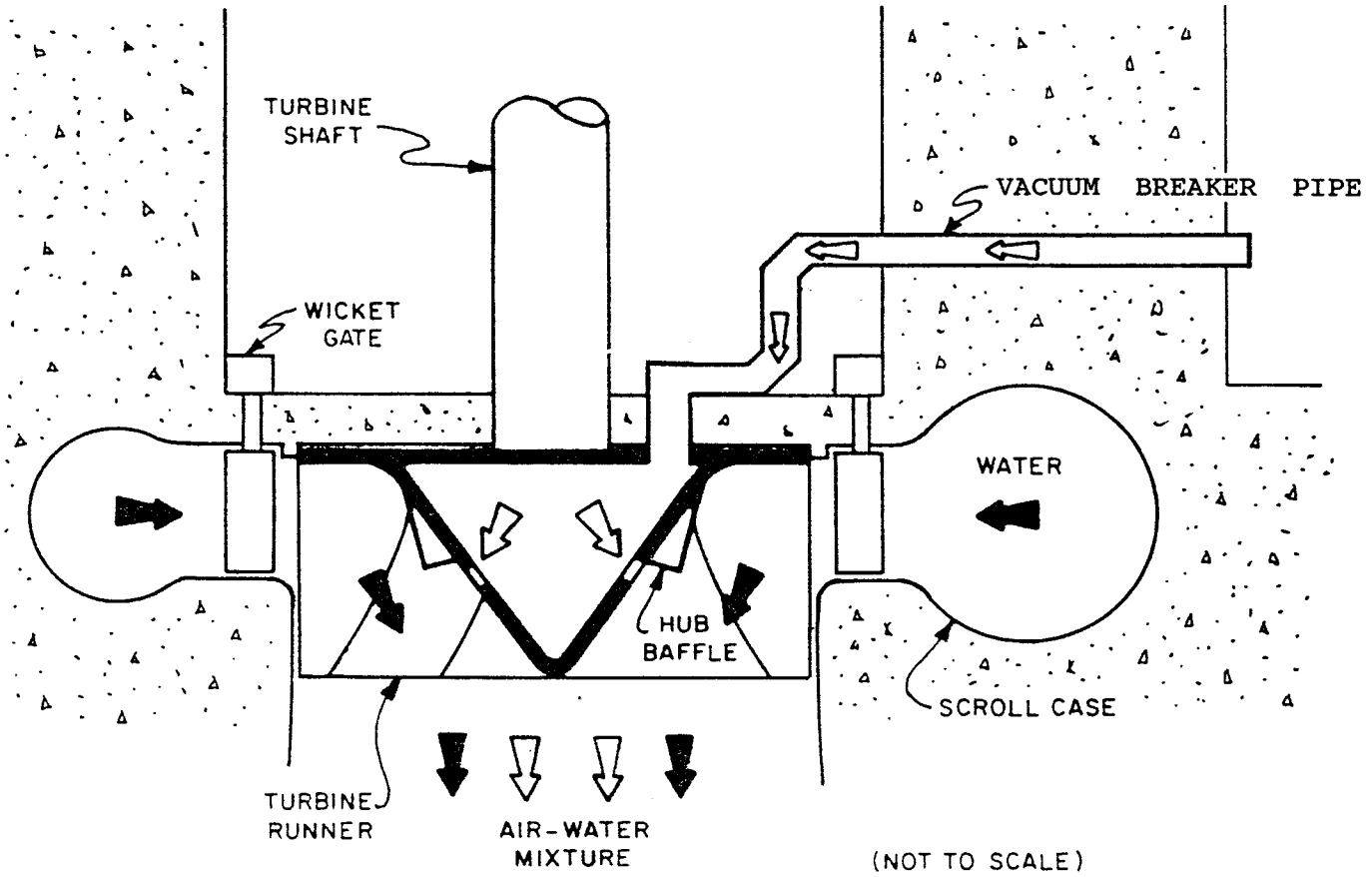


Figure 6-29. Turbine Venting Through the Vacuum Breaker

effects and the problems encountered are the same as if the air was induced (i.e., proper air/water ratios must be observed, cavitation problems may arise).

Working Principles. The working principles of aeration via the vacuum breaker are nearly identical to those of draft tube venting. However, predicting hub pressures is considerably more difficult than predicting draft tube pressure.

Limitations, Constraints, Trade-offs. In addition to the same constraints and trade-offs associated with draft tube venting, the turbine headcover is usually a congested area, and severe constraints may apply when sizing pipe to fit the available area.

Aeration via the vacuum breaker has also been associated with increased cavitation damage on older turbine runners and increased wear on turbine bearings due to abnormal pressures the machinery experiences while gas is injected. At TVA's Norris hydroplant, where the runners are approximately 50-years old and are made of cast steel, cavitation repair was normally performed every 5-years prior to aeration. Following the initiation of turbine venting, this same amount of repair was necessary each year for the first few years at a cost of $50,000 per unit. As the existing carbon steel was overlaid with stainless steel welds, however, this cavitation damage decreased. For 1989, no repair was necessary.

Major Obstacles To Installation. As a general rule, only relatively small amounts of air can be induced through the vacuum breaker under normal conditions. To increase the volume of injected air, friction losses in the piping must be reduced. Generally, this requires for re-sizing of the system and substantial renovation. The routing of large-diameter piping in existing powerhouses and fitting it to the headcover can be a formidable task.

Environmental Effects. If air is aspirated naturally through the vacuum breaker and noise suppression devices are part of the design, no adverse environmental effects should occur. If compressors and/or pure oxygen is applied, both noise and visual impact could be problems.

Equipment Life Expectancy. Present data indicate that increased runner cavitation can be expected, but quantification is difficult. If compressors are used, a 25- to 30-year life is reasonable, provided major overhauls occur approximately every 10-years and the equipment is only used for aeration. It should be remembered this equipment need only function during periods of low DO, perhaps 5 months each year. See Appendix G for a discussion concerning the life expectancy of on-site oxygen generation equipment.

Safety. No additional safety hazards are associated with naturally aspirating vacuum breaker aeration systems. If baffles are removed seasonally, normal hazards exist when working in the vicinity of the runner. If compressors are involved, typical "moving machinery" hazards exist, along with the heat associated with compression. If pure oxygen is used, extra care must be taken not to introduce flammable materials and sources of ignition.

Possible Modes of Failure. Very few modes of failure exist for naturally aspirated vacuum breaker systems. If operators fail to open the vent valve, the system will not aspirate. If baffles are not fastened well, they may break loose, reducing aeration efficiency. If compressors are incorporated into the design, normal maintenance will lessen the chance of failure. Typical risks with oxygen systems include a stoppage of delivery from commercial vendors or a breakdown with on-site generation equipment.

The most unpredictable source of failure is system performance. In spite of the fact that the technique has worked at other locations, the methods of predicting system performance have not advanced far enough to be reliable. In addition, because systems vented to the atmosphere have a natural limit on their ability to aerate, if incoming DO levels worsen, the aeration system cannot be easily expanded to meet the demand.

Risk Analysis. In spite of the fact that the method has been tested at several facilities, the procedures involved when predicting oxygen uptake using vacuum breaker aeration systems are not well defined. Work is continuing to better understand the flow characteristics about the runner, and to design better self-aerating turbines. Until

this is accomplished, other aeration techniques should be considered more reliable.

Sizing. The only known procedure recommended for vacuum breaker design is to measure the air flow in the existing system with the vacuum breaker valve blocked open, predict the port pressure, and design the supply piping using the same procedure as detailed for draft tube venting systems. However, because the addition of increased quantities of air through the hub produces unpredictable results, this procedure is associated with a considerable degree of uncertainty and risk.

Costs. As with draft tube venting systems, the cost will be very site-specific. Although some savings may be realized by not routing the supply piping through the spiral case, the majority of the costs are energy-related, and will be similar in both techniques.

Case Studies. The TVA has applied various forms of vacuum breaker venting for DO enhancement at many of their installations, with mixed success. At South Holston Dam, the vacuum breaker ports on the 35 MW unit were relocated farther down the hub and baffles were added. Unfortunately, the baffles aspirated no air at low gate openings (by design) and the unit vibrated so badly at these openings that the baffles were removed and the parts returned to their original locations. An additional 8-inch diameter opening was cut through the unit headcover to bypass the vacuum breaker valve, and air is supplied through a short piece of pipe equipped with a muffler to reduce the noise. Enough air is now induced to increase the DO in the 3,500 CFS of water discharged by about 2 mg/L when the incoming DO is near zero. No significant cavitation damage attributed to aeration has been observed on the runner.

The most successful vacuum breaker aeration system using hub baffles has been on the two 50 MW units at TVA's Norris Dam on the Clinch River. After several early designs were tested and improved, bolt-on baffles were designed and have been in use for several years. The cylindrically wedge-shaped baffles protrude approximately 5.5-inches, and induce enough air to add from 2 mg/L to 4 mg/L to the discharge. The baffles and induced air reduce unit efficiency less than 0.5%.

The two units, however, have initially experienced an accelerated rate of cavitation damage, and an expanded cavitation area. Recent inspections, however, indicate that cavitation damage is declining as the damaged areas are overlaid with stainless steel.

TVA has also experimented with forced air injection at several dams with varying results (Rev. 6-45, 6-46, and 6-47). In most cases, tests were conducted using portable compressors. Small (1-2 mg/L) increases in discharge DO were obtained by this method, but lack of space for the compressors and the accompanying piping, the necessity of cutting through existing concrete to install air passages, the high initial capital costs, and the relatively high cost of power to operate the compressors precluded their permanent use. At Norris Dam, the use of a compressor to force air through the vacuum breaker system was associated with excessive, hard-to-repair cavitation damage on the runner. At other dams, the compressed air systems were not operated long enough to assess their effect on cavitation damage.

A compressed air system connected to the vacuum breaker piping is in use at TVA's Tim's Ford Dam to increase DO about 3 mg/L in the discharge from the mixed flow unit. The compressor at Tim's Ford is housed in a small, separate building outside the plant. Air is fed through piping routed around the building to a point near where the vacuum breaker line enters the headcover. The controls for the compressor at Tim's Ford are tied in to the water flowmeter so that only enough air is admitted to raise the discharge DO a desired 3 mg/L. This eliminates the energy losses encountered when adding more air than is needed. Only nominal cavitation damage has been noted.

Selective Withdrawal

Reservoirs are usually constructed and operated for purposes of flood control, power generation, and water supply. Reservoirs have also been operated to control temperature, salinity, turbidity, dissolved oxygen, as well as other water quality parameters within the reservoir and in the tailwater. This is accomplished by drawing water from the reservoir at selected depths where the water quality may be more desirable. This practice, generally referred to as selective withdrawal, is one alternative for improving DO immediately down-

stream of reservoirs. To date, the majority of selective withdrawal applications has been on non-power projects.

Physical Aspects. The fundamental component of a selective withdrawal system is the "wet well" that extends over a large part of the depth of the impoundment. Water from the reservoir enters the well by one or more controlled openings in the side of the well at different elevations. At the bottom of the well the water enters an outflow conduit which passes downstream through the dam. The detailed geometry of the reservoir outlet is site specific and depends heavily on the purpose of the project; however, most can be classified as one of three types: free standing vertical well, inclined well along an embankment, or vertical well supported by the face of the dam or powerhouse. Examples of each type are shown in Figures 6-30 to 6-32, respectively.

For selective withdrawal of surface water the submerged weir could be classified as a fourth type of discharge structure. An example is shown in Figure 6-33. In this case a weir is constructed a short distance upstream, either across the reservoir or around the outlets. Based on the degree of reservoir stratification, the elevation of the top of the weir is selected to "skim off" the surface water of the approaching flow. In this manner the pool between the submerged weir and the outlets forms a large wet well. A submerged weir can be constructed using one or a combination of physical arrangements, including a rubble-mound, concrete wall, steel sheet-pile, cellular-steel cofferdam, or a cable-supported membrane curtain.

Working Principles.
In an existing reservoir constructed for generating power, turbine intakes are usually located near the bottom of the reservoir to take advantage of the available head, satisfy submergence requirements, and reduce the penstock length. One way to increase DO in the discharge is simply to withdraw water from the upper layers of the reservoir. This can be accomplished by constructing intake structures that draw water at an elevation above the thermocline or low DO levels.

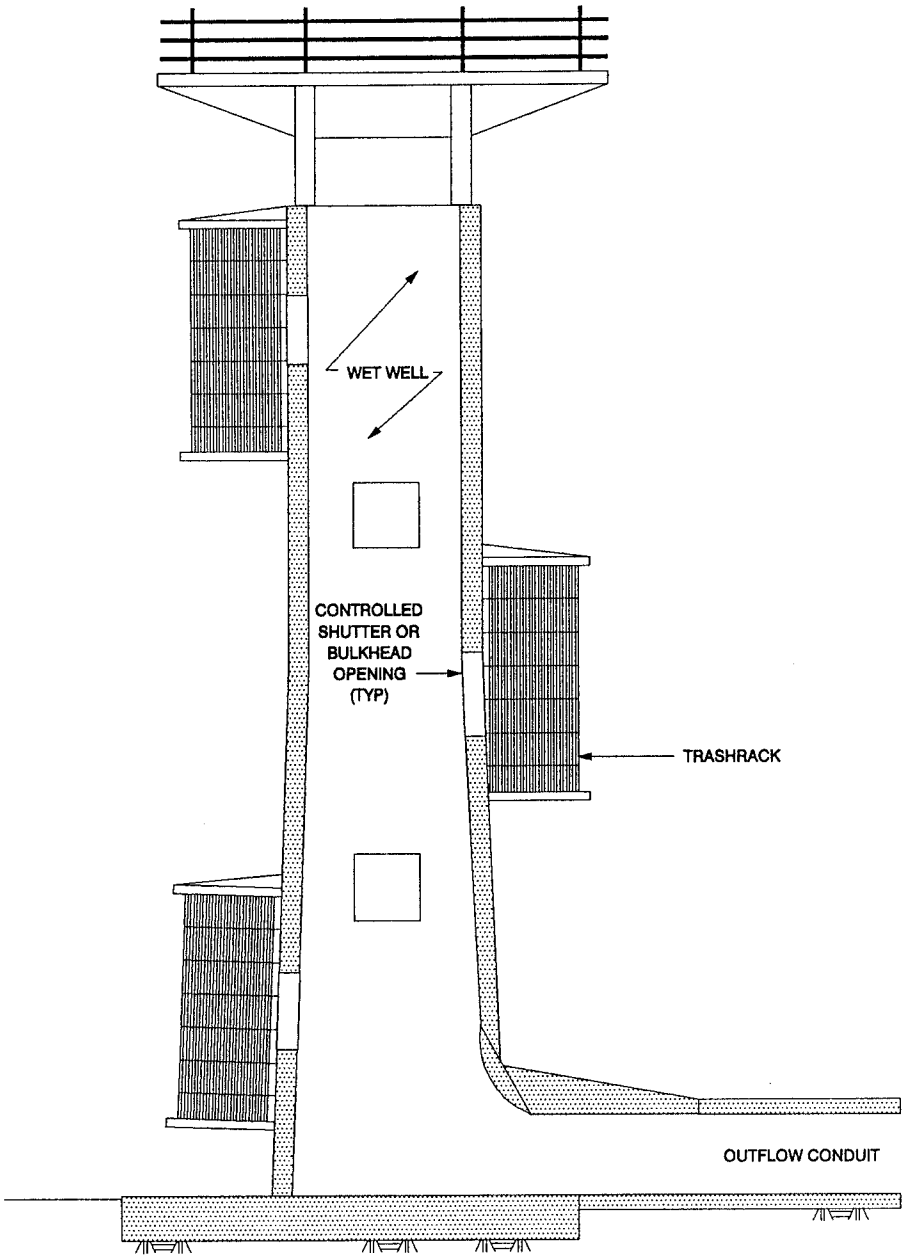


Figure 6-30. Sefective Withdrawal with Free Standing Vertical Well.

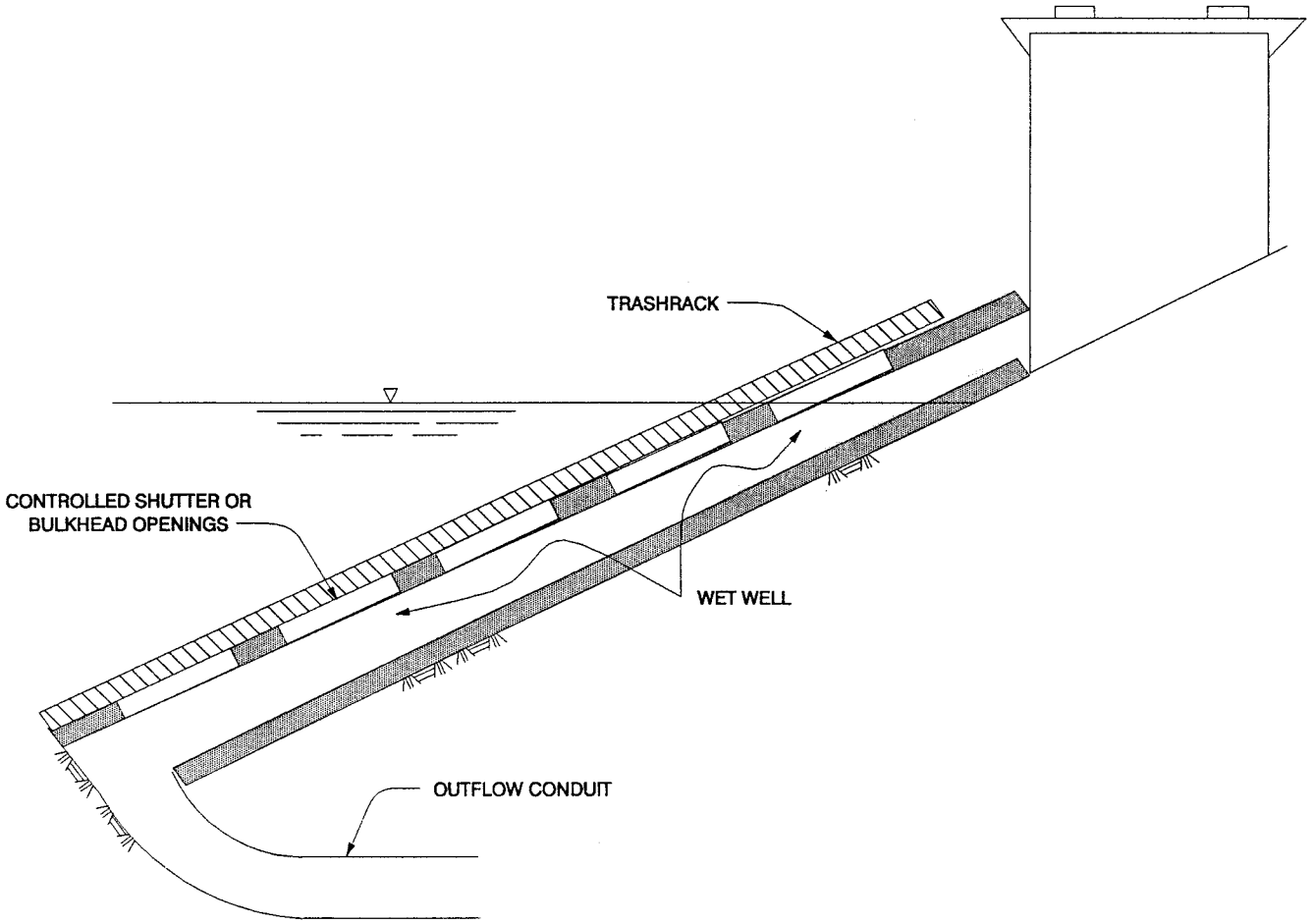


Figure 6-31. Selective Withdrawal with Inclined Well Along an Embankment.

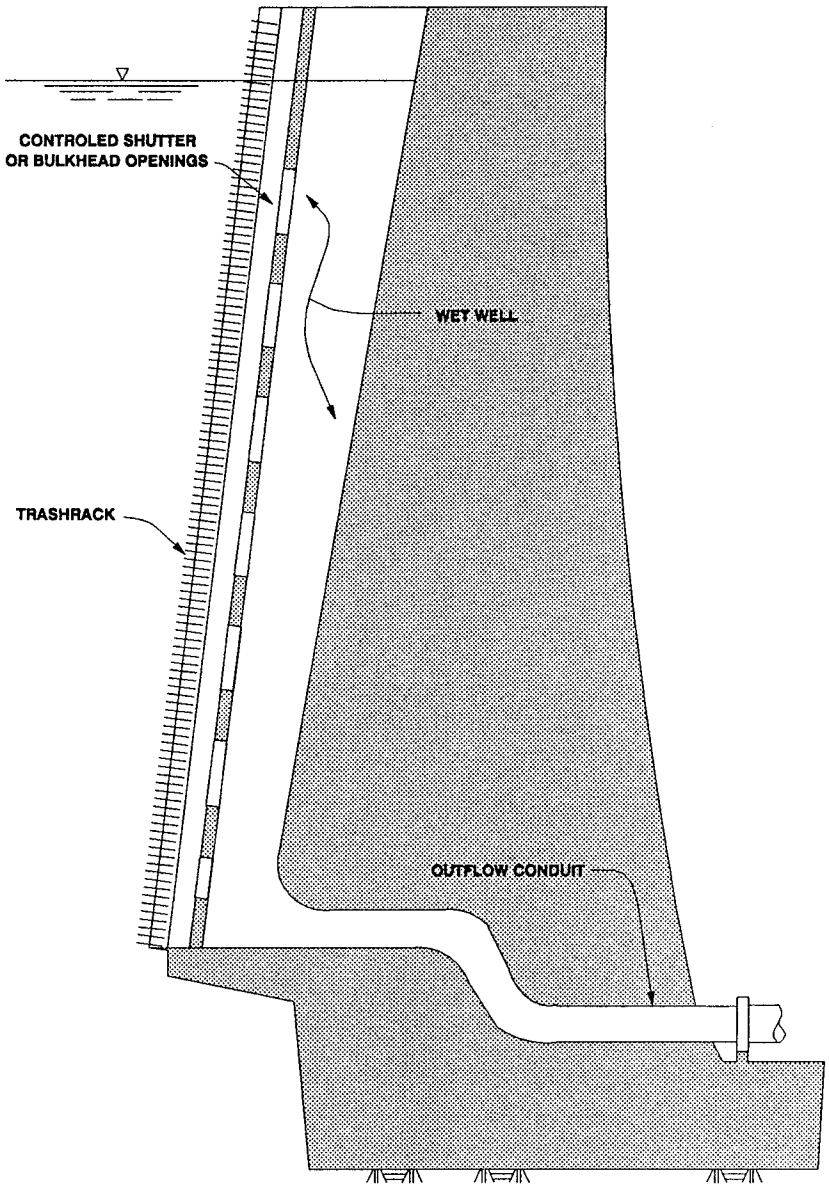


Figure 6-32. Selective Withdrawal with Well Supported by Face of Dam or Powerhouse.

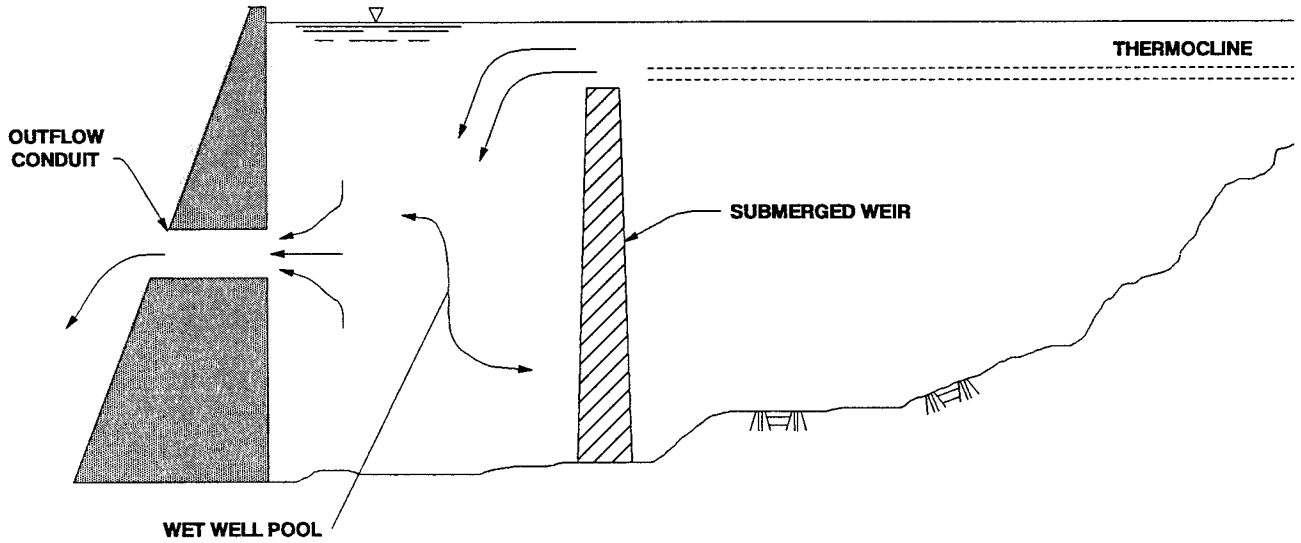


Figure 6-33. Selective Withdrawal with Submerged Weir.

The feasibility of using selective withdrawal as a means for improving DO depends on many factors. Among these are the configuration of the discharge structure; reservoir stratification cycle and energy budget; reservoir water quality characteristics and distribution; economics of modifications; and, competing reservoir objectives.

Limitations, Constraints, and Trade-Offs. Selective withdrawal as an alternative for water quality control has become a design objective of many reservoirs. However, not all existing control structures have outlet works suitable for selective withdrawal. In some cases wet wells or submerged skimmer weirs have been retrofitted to existing structures to improve the selective withdrawal capability. Where selective withdrawal is structurally feasible, there may be competing demands for the quality of water to be drawn from the reservoir. For example, lower, colder water may be desirable for cold water fisheries while warmer, more oxygen rich surface water may be more desirable for DO improvement.

For both new and retrofitted outlets, routing the flow through controlled openings will result in additional energy losses, which will reduce the outlet capacity. For hydroelectric installations, the net head available for power generation will be lower, reducing the generation capacity. Also, withdrawal from the upper levels of the reservoir can cause the temperature of the water entering the turbine intakes to increase significantly. If cooling water for the generators is drawn from the intake flow, the temperature increase can reduce generator capacity and power output from the plant.

Major Obstacles to Installation. Obstacles to installation apply mostly to existing projects. Retrofitting an existing dam for selective withdrawal may involve draining the reservoir below the level of construction, using cofferdams to locally dewater the intakes, use of divers for underwater construction, or a combination of these procedures. The cost of such procedures and the revenue lost due to the interruption of power or other project uses may be prohibitive. Depending on the project, it may be possible to retrofit the outlets without interrupting service. A good example is the Flaming Gorge Dam on the Green River in Utah (Ref. 6-48). In this case, wet well towers were fabricated on shore, floated into place,

positioned by ballast, and attached to support brackets on the face of the dam, all without interrupting the turbine operation.

For both new and existing projects the use of high level intakes and submerged weirs do not easily lend themselves to reservoirs where the water level fluctuates widely during the year. Also, navigation requirements may prohibit the use of submerged skimmer weirs on many waterways.

Environmental Effects. Selective withdrawal to improve discharge water quality, particularly DO, is most effective when the reservoir is stratified. The degree of effectiveness, as measured by improved DO level, depends on the strength of stratification and location of the thermocline with respect to the intakes. Duration and strength of stratification in a reservoir depend on the meteorology and mechanical energy associated with inflow and outflow. Meteorological conditions control the rate of energy transfer at the air-water interface. This energy transfer consists of radiation heating and convective cooling as well as mechanical mixing due to the wind action. A reservoir goes through an annual cycle of stratification and overturning which affects water quality both in the reservoir and in the tailwater. Fischer, et al. (Ref. 6-49) give a detailed discussion of reservoir behavior and the resultant water quality changes. They also provide mathematical tools for analysis of various thermal and mechanical processes in reservoirs.

Austin and Gray (Ref. 6-50) report on the performance of multilevel outlet works at four reservoirs constructed by the Bureau of Reclamation. Selective withdrawal was employed at these projects to control objectionable taste, odor and color, as well as maintaining a cool release temperature for salmon spawning in the downstream reach of the river. The projects are Cachuma, Casitas, Folsom, and Whiskeytown, all in California. The first three projects are briefly described later in this section as Case Studies.

The Corps of Engineers has successfully employed selective withdrawal at a number of projects including Lost Creek Reservoir, Oregon; DeGray Lake, Arkansas; Beltzville Lake, Pennsylvania; and Stockton Lake, Missouri. Water quality objectives at these projects include

controlling in-lake turbidity, maintaining warmwater fisheries, and providing adequate dissolved oxygen downstream (Ref. 6-51).

Low DO problems in a reservoir may be alleviated to some extent by discharging the undesirable hypolimnion water through the bottom outlet. Consequently, reservoir water quality problems become tailwater quality problems. Coordinated release from various depths may be a more balanced way of controlling water quality in the reservoir as well as in the tailwater. However, experience in California (Ref. 6-50) indicates that use of multilevel outlets alone is not the complete solution to water quality problems in reservoirs. Supplemental means such as copper sulfate treatment for algae control and forced destratification may also be necessary.

When large vertical water quality gradients exist in a reservoir, selective withdrawal may produce a release which meets downstream water quality objectives. However, as the reservoir goes through its annual cycle, the vertical gradients weaken and meeting downstream water quality objectives by selective withdrawal may no longer be a viable alternative. Brown, et al. (Ref. 6-52) evaluated the selective withdrawal capabilities of the Columbia Dam, Duck River, Tennessee, using a mathematical model. Their analysis shows that selective withdrawal is most effective under strong density gradient with distinct vertical water quality variations.

Equipment Life Expectancy. Requirements for the annual inspection and maintenance of selective withdrawal outlets are basically the same as those recommended for any outlet facility; details are not given here. Examples, however, can be obtained by contacting any agency which operates dams and reservoirs (e.g., Corps of Engineers, Bureau of Reclamation, Tennessee Valley Authority, etc.). If inspection and maintenance are performed as specified, the outlet equipment should last the entire design life of the project.

Safety. Safety requirements for selective withdrawal can be satisfied by providing guard booms and warning signs that limit access to regions near intakes where surface velocities may be high.

Possible Modes of Failure. If the spacing between the openings of a selective withdrawal structure are large, selectivity is limited and may not allow the withdrawal of water at the desired reservoir depth. For outlets located near the bottom of the reservoir, siltation may obstruct and prevent the operation of control gates. If care is not taken to keep trashracks clean, similar obstructions may be caused by floating debris and vegetation. For the submerged weir, rubble-mounds should be graded to prevent significant seepage of hypolimnion flows towards outlets. The pool between the weir and the dam may restratify if its volume is large compared to the volume of water passing through the outlets. Also, fixed submerged weirs will not be effective in reservoirs which fluctuate over a large range of surface elevations.

Sizing. A register of projects in the United States that include capabilities for selective withdrawal was compiled and published by the American Society of Civil Engineers (ASCE) Task Committee on Outlet Works in 1970 (Ref. 6-66). An update of the register for new and retrofitted projects since 1970, as well as overseas work, is needed. The register contains 90 dams and identifies the major design features of the outlets for each. Operating agencies from whom detailed information may be obtained are also given. Most of the dams were built by either the Corps of Engineers or the Bureau of Reclamation. Each of these agencies has developed design procedures for selective withdrawal based on the experience obtained in sizing the outlets. For the Corps, a recent summary of recommended design procedures is given by Holland (Ref. 6-65).

The design for selective withdrawal usually begins with theoretical analyses to predict the seasonal behavior of the reservoir and downstream river reaches. Such analyses can include state-of-the-art mathematical models to determine the flow, water elevation, and spatial distributions for temperature, DO, and other water quality parameters. Data that are required to establish initial and boundary conditions in the analyses include the reservoir and downstream river geometry, hydraulic characteristics of the proposed withdrawal structures, hydrologic and meteorologic measurements, and inflow of water quality constituents.

After calibration and verification, the models are used to determine the number of outlets, their elevation, and flow needed to obtain the desired water quality in the reservoir and downstream.

Some have combined these models with dynamic programming procedures to develop optimal strategies for the seasonal operation of the selective withdrawal structures (Ref. 6-53 and 6-54). Given water usage and operational constrains, the optimal strategy is defined as the release schedule that minimizes the differences between the desired water quality and that which is obtained by selectively opening the various outlets.

Detailed hydraulic design of the outlets can proceed once the number, elevation, and flow are known. The size and geometry of the outlets will depend largely on the discharge requirements, purpose of the reservoir, site conditions, and the arrangement of other project structures. Guidance can be obtained from the design criteria for outlets used by the Corps of Engineers (Ref. 6-55) and the Bureau of Reclamation (Ref. 6-56). Results from physical hydraulic model studies used to design existing selective withdrawal outlets also can provide valuable information (e.g., contact the agencies listed in the ASCE register).

In general, multi-level intakes are costly to construct, particularly in retrofit situations. Any such intakes must be carefully designed to obtain the flexibility required for water quality control with minimum hydraulic losses over the range of expected operational conditions. Depending on the level of design uncertainty, one or more physical hydraulic model studies may be required to confirm the operation of the proposed outlets and the selective withdrawal scheme. These may vary from a small simple model to test geometric configurations of the outlet flow passage, to a large comprehensive model that includes the thermo-hydrodynamic behavior of the upstream reservoir and downstream river.

Costs. Except for impoundments constructed for water supply, irrigation, and fish propagation, the original design studies for the outlets of many projects did not emphasize the cost and benefits associated with the quality of water released downstream. It has

only been through the increased awareness of the detrimental effects of low dissolved oxygen and other release characteristics (e.g., temperature, turbidity, etc.) that attention has focused on the need to include such factors in the economic analysis of all impoundments. The cost and economic sensitivity of selective withdrawal will depend primarily on:

a. New vs. existing impoundments;
b. The purpose(s) of the project;
c. The type of outlet required;
d. Operation and maintenance requirements;
e. The cost of alternative methods to improve water quality.

Due to special construction requirements and the possible interruption of services, it will usually be more costly to retrofit existing projects compared to new projects. The severity of service interruptions, if any, will depend on the purpose of the project and the cost of providing services from alternate sources (e.g., for power and water supply).

For a given project the cost of several different withdrawal configurations should be considered, including different wet well and control gate arrangements attached directly to the outlet, and submerged weirs. Case studies referenced herein should provide several ideas for different arrangements.
Unfortunately, except for Flaming Gorge Dam, the cost of selective withdrawal for the case studies summarized herein are not readily available for publication. At Flaming Gorge, the cost of construction for retrofitting the power intakes was reported as $4.2 million (1978 dollars) (Ref. 6-48).

Case Studies. A few examples have been chosen from nearly one hundred projects in the United States that have capabilities for selective withdrawal. To stress the site specific nature of this method for improving downstream DO, an effort has been made to provide a wide range of examples. A review of this experience needs to include not only the basic design features of multilevel outlets, but also their relative successes in meeting design objectives.

Cachuma Dam, Santa Ynez River, California (Ref. 6-50):
Cachuma Dam was built primarily for water supply. Although dissolved oxygen was a factor, the major design criteria for selective withdrawal were based on water taste and odor. The outlet type is a free standing well with 5 openings located throughout its depth controlled by slide gates. Withdrawal during the summer and fall is at a level above the thermocline but below the surface region where algae growth is heavy. The level is adjusted approximately every 30-days depending on reservoir conditions. The only problem encountered is with the lowest gate, which has become unusable due to reservoir siltation.

Casitas Dam, Coyote Creek, California (Ref. 6-50):
Casitas Dam was also built for water supply, hence design criteria and operation for selective withdrawal are basically the same as that for Cachuma Dam. The outlet type is an inclined well on the dam embankment with 9 openings along its depth controlled by high pressure gates. Experience has found that the spacing between gates is somewhat too large and that there have been times when the capability to be more selective of the withdrawal level would have been advantageous. To alleviate this problem the operating agency has retrofitted a temporary "stack" over the gates to enhance withdrawal from levels between the gates.

Folsom Dam, American River, California (Ref. 6-50):
Folsom Dam was built for power, irrigation, flood control, recreation, and navigation. A cold water fishery is also located below the project. Warming of water in the reservoir was greater than pre-construction expectations, resulting in temperatures that exceeded limits required for the fishery. The problem occurred in late summer and fall when the reservoir surface was close to the intakes due to storage consumption. To alleviate the problem "shutters" were retrofitted in guides attached to the existing trashracks in front of the power intakes, thus creating a vertical well on the face of the dam. Selective withdrawal is achieved by raising or lowering the shutters to draw off water at the desired elevation. To satisfy the fishery requirements, flow is drawn from levels near the surface in the spring and early summer when water temperatures are typically satisfactory. In late summer and fall when surface temperatures

become high, the shutters are adjusted to draw the conserved cooler water from lower levels in the reservoir.

Libby Dam, Kootenai River, Montana (Ref. 6-57):
Libby Dam was built for power, flood control, and related uses. Selective withdrawal was required to maintain pre-construction temperature and dissolved oxygen levels in the downstream tailwater. The original project design did not include plans for selective withdrawal. To provide this capability, bulkheads were retrofitted in front of the power intakes, again forming a vertical well on the face of the dam. The withdrawal level is controlled by the elevation of the top of the bulkheads.

Dworshak Dam, Clearwater River, Idaho (Ref. 6-57):
Dworshak Dam was built for power, flood control, and related uses. Selective withdrawal was needed to satisfy dissolved oxygen and temperature requirements for fish populations downstream. In a fashion similar to that for Libby Dam, an outlet well was formed on the face of the dam by retrofitting the power intakes with submerged bulkheads.

Lost Creek Dam, Rogue River Basin, Oregon (Ref. 6-57):
Lost Creek Dam was built for power, flood control, and related uses. Selective withdrawal was required to control water temperature, dissolved oxygen and turbidity in the downstream reach. The outlet type is a free standing vertical well with 4 controlled inflow ports. The well supplies flow to both power intakes and regulating outlet gates.

Dickey Dam, Saint John River, Maine (Ref. 6-58 and 6-59):
Although not constructed at this time, Dickey Dam is planned for power, flood control, and recreation. The outlets have been designed to provide selective withdrawal to match the existing natural temperature regime of the downstream tailwater. The project is to include both a multipurpose freestanding vertical well and vertical wells attached to face of the dam. Flow into the wells is to be controlled by bulkhead "selector" gates which can be raised or lowered to draw water from the desired reservoir depth. A unique feature of this project is that it includes pump-turbines, hence the selector gates

also must be designed to distribute the water back into the reservoir and sustain the hydraulic loads due to the reverse flow.

Sutton Dam, Elk River, West Virginia (Ref. 6-60):
Sutton Dam was built for flood control, pollution abatement, fish propagation, and recreation. Selective withdrawal was not included in the original project but was later found necessary to reduce turbidity and increase the temperature and dissolved oxygen of water released to the downstream reach. Hydraulic model studies were performed for a semicircular riser retrofitted in front of the intake for one of the low level outlet sluice gates, thus forming a vertical well on the face of the dam. The riser draws water from the epilimnion of the reservoir, thus satisfying the downstream water quality requirements.

Flaming Gorge Dam, Green River, Utah (Ref. 6-48):
The Flaming Gorge Project is a major unit of the Colorado River Storage Project and is managed primarily for power production. After the reservoir was filled, hypolimnion releases through the turbines caused a reduction of fish populations in the downstream water courses. To increase the dissolved oxygen and temperature to their desired support levels, selective withdrawal capabilities were retrofitted to the power outlets. This was accomplished by installing a square-shaped tower over the existing trash racks for each of the three intakes, thus creating vertical wells on the face of the dam. Each tower is covered with a corrugated steel skin and includes moveable shutters that allow water to be withdrawn from the reservoir over an elevation range of 174-ft.

Wellington Dam, Collie River, Australia:
This dam has been the subject of many investigations, including selective withdrawal for the purpose of formulating a scour policy (Ref. 6-61 and 6-62). The dam has a water supply off-take at mid-depth and a scour valve at the base. The first high flows of the season in the Collie River are characterized by high salinity and a low temperature. The combined effects of salinity and temperature create an underflow that is allowed to move along the reservoir bottom, undisturbed. The underflow travels the entire length of the reservoir and is withdrawn at the base of the dam through the scour

valve. Field measurements show that selective withdrawal strategy has considerably improved the quality of water in the reservoir.

Submerged Skimmer Weirs:
Although the submerged skimmer weir discussed earlier is less common and lacks operational flexibility, it has been used for several projects in the United States. Two applications are Stockton Dam on the Sac River and Harry S. Truman Dam on the Osage River, both in Missouri (Ref. 6-63). The projects are primarily for power and flood control. After the dams were placed in operation, it became apparent that selective withdrawal was needed to increase the water temperature and dissolved oxygen for fish populations in the downstream reaches. Submerged rock weirs were installed a short distance upstream of the dams by dumping material from barges. The crests were constructed slightly above the natural thermocline that occurred during the late summer and fall. The weirs skim water from the high temperature, oxygen rich upper levels of the reservoir and creates deep "epilimnion pools" between the weirs and the dams, which supply flow to the power intakes.

For rock weirs, care should be taken to include the proper gradation of fill material. Although the voids were eventually filled with reservoir sediments, the early performance of the weir at Stockton Dam, constructed with large fill material, was hindered by hypolimnion flows seeping through the submerged rock. Although not a factor at the Stockton and Harry S. Truman Dams, if flow through the outlets of the dam is small, the pool between the weir and the dam may restratify, which has also been known to occur.

Whereas an abundance of design information can be obtained from agencies that operate reservoirs, the published data from water quality monitoring programs used to calibrate, verify, and update operating scenarios for selective withdrawal are limited.

6.3 RESERVOIR TECHNIQUES

Reservoir Techniques encompass aeration systems located far upstream of the dam. Because of their similarity to the technique applied to destratify inland lakes, Reservoir Techniques encompass some of the

earliest attempts to enrich hydropower discharges. Of the many techniques tested over the years, only two general approaches have been shown to be practical for DO enhancement: reservoir destratification and hypolimnion aeration. Reservoir destratification may be a practical alternative provided favorable site-specific conditions exist. Several destratification techniques have been tested, with air injection being the more commonly accepted approach. A closely related and relatively new approach pronounced by the Australians to be extremely successful is that of stratification prevention. By applying a considerably smaller amount of effort early-on, stratification can be prevented, thereby avoiding low-level dissolved oxygen problems. (Ref. 6-67)

The Corp of Engineers has shown that oxygen injection techniques for hypolimnion aeration can be successfully applied on a large scale. Their installation at Richard B. Russell in Georgia has been able to increase the DO level of the hypolimnion from an initial level less than 3 mg/L, to an aerated level greater than 9 mg/L, with an average transfer efficiency of approximately 75%. Transfer efficiencies have been as high as 96%. (Ref. 6-40)

The following sections will discuss each of the two approaches in detail.

Reservoir Destratification

Destratification has been attempted at a number of reservoirs in the past, and has met with mixed success. Although the majority of previous applications have not been concerned with improving the quality of hydroelectric discharges, they are similar in that the end goal has been to destratify the reservoir and to improve overall water quality. On larger hydroelectric reservoirs, destratification techniques may only be practical in a zone immediately upstream from the dam, and not throughout the entire reservoir.

The technique received considerable attention in the U.S. during the 1960s and 1970s; more recent applications, however, are unknown. The Australians, however, have advanced the technology to where it can be considered one of the best options for water quality improvement in certain situations.

The main advantages of destratification are it is relatively inexpensive (Ref. 6-68) and it improves other water quality characteristics by reducing levels of taste, odor, corrosivity, phosphates, dissolved iron, and manganese. The main disadvantage of destratification is it increases the temperature of the discharge, which may adversely affect downstream water uses, including industrial cooling water applications and coldwater fisheries.

Physical Aspects. Because stratification of the reservoir is a major factor leading to low DO levels, destratification is a viable means of improving reservoir discharges. Destratification involves the input of mixing energy to expose the colder hypolimnion water to the atmosphere, raising both the DO level and the temperature. The energy is supplied either by mechanical pumping or a compressed air system, and is generally applied at the deepest point in the reservoir. In certain cases, total reservoir destratification can be accomplished in a matter of days, if not hours, provided sufficient energy is input. Mechanical pumps such as those used by Irwin, et al., (Ref. 6-69), Figure 6-34, or simple aeration devices like a single pipe injecting air via diffusers near the bottom of the reservoir (Ref. 6-70) have been successfully applied. The air-systems are supplied by shore-mounted compressors.

Working Principles. To re-distribute the heat content uniformly throughout the reservoir, mixing energy is generally applied to the cooler, denser water, transferring it to the surface; the warmer, less dense water is forced to the lower depths. As the density layers mix and become uniform, dissolved oxygen also becomes homogenous. A critical working principle is that the simple vertical transport of water is not sufficient to accomplish destratification; if insufficient energy is applied, the water will seek equilibrium and return to its original position. In addition to the vertical transport, adequate mixing energy must also be supplied, requiring a velocity gradient. The greater the density gradient, the greater the velocity gradient required for mixing. Thus, for efficient destratification, mixing should be initiated when the density differential is lowest, i.e., before the reservoir actually stratifies.

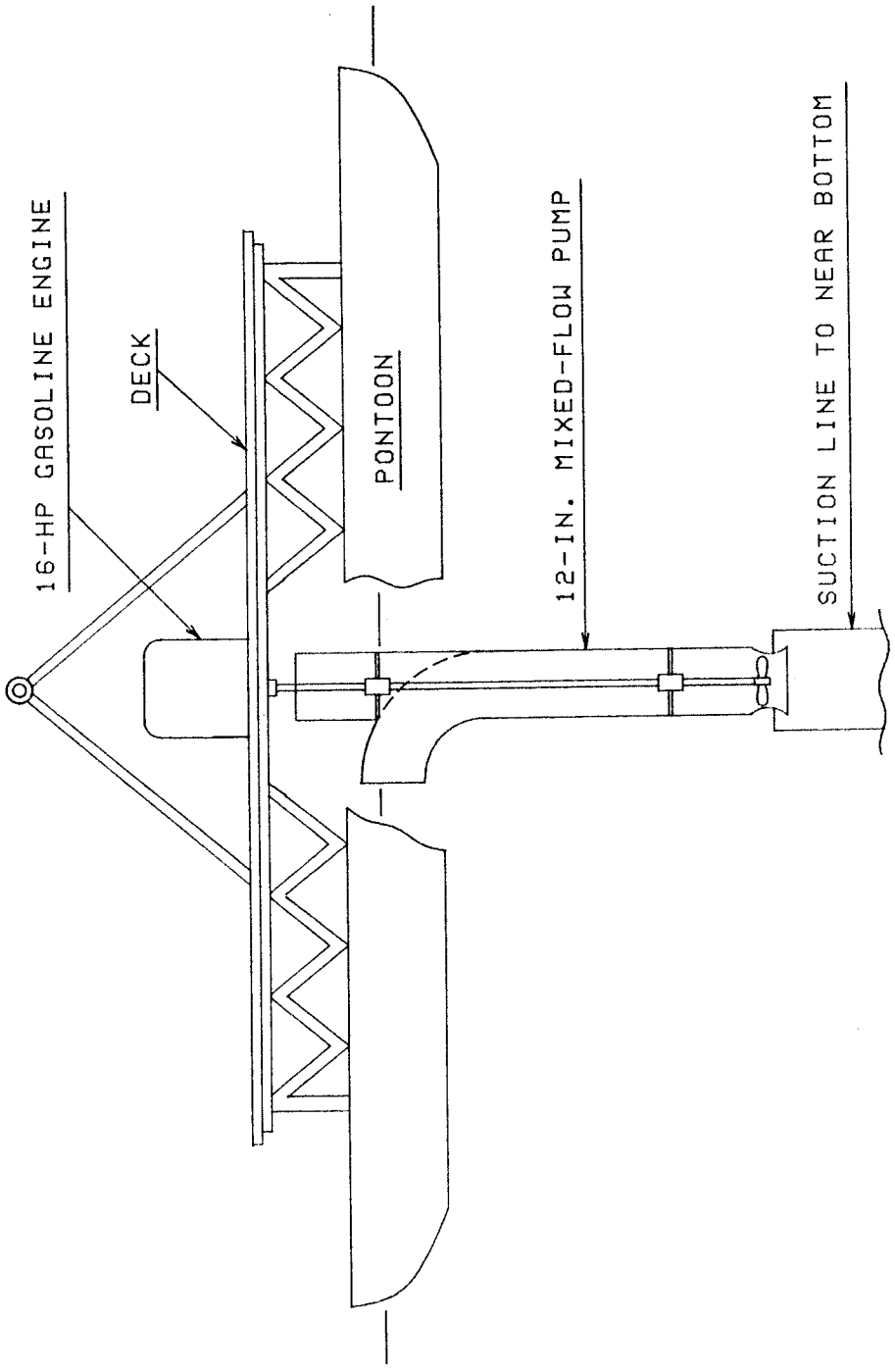


Figure 6-34. Mechanical Surface Water Pump (Ref. 6-69)

The following working principles should be considered when designing a reservoir destratification system:

- Irrespective of the mixing device, very little oxygen is actually transferred to the water. Destratification mixes the existing dissolved oxygen uniformly throughout the lake. A small amount of oxygenation will be gained at the surface.
- If compressed air is used, the diffusers should be designed to maximize mixing, rather than oxygen transfer.
- The spacing of the mixing system is inversely related to the density differential of the water to be destratified, because the active mixing zone increases with smaller density differentials.
- Large diameter, slowly rotating propellers move more water per horsepower than small diameter, high tip speed impellers, because the latter expend more energy in acceleration.
- High tip speed impellers are applicable to destratification schemes because they provide high velocity gradients and better mixing than low speed impellers.
- A well-designed mixing system will employ the plume to entrain the surrounding water.

Limitations, Constraints, and Trade-offs. Destratification techniques have few limitations. Reservoirs can be destratified irrespective of size, provided enough mixing energy is supplied at the proper locations. However, if the bottom sediments are easily disturbed, it may be necessary to distribute mixing energy over a larger area in order not to suspend settled material. Another constraint that may exist is the local fishery. If species exist, either downstream and/or in the reservoir that depend on the cooler temperatures of the metalimnion and hypolimnion, destratification may be possible to achieve, but undesirable because of the effect of the temperature increase on the local fishery. In some cases, upstream migrating fish have come to depend on the cooler releases from the hypolimnion. Once a reservoir is destratified, releases are warmer, affecting not only the resident species, but those that migrate.

A final limitation to destratification is that the total dissolved oxygen content of the reservoir may not be large enough to meet minimum water quality standards after mixing. It is possible that after mixing, the DO content of the mixed reservoir is still below the imposed standards. This situation is illustrated in Figure 6-35, where the temperature and DO content of Stewart Hollow Lake is depicted by Irwin, et al., (Ref. 6-69) before mechanical pumping and afterwards.

Major Obstacles To Installation. The major obstacle to successful destratification is that no two reservoirs are alike. The lack of numerous successful case histories for sites having similar characteristics is a problem, along with a shortage of design criteria. Two excellent sources for design guidance, however, are by P. L. Johnson (Ref. 6-90) and Lorenzen and Fast (Ref. 6-77).

If a cold water fishery habitat must be maintained in the reservoir or downstream of the dam, it is unlikely that destratification techniques can be applied. If bottom sediments are easily displaced, care must be taken to elevate mixing plumes well above any level of influence.

Finally, the more obvious obstacles to installation include the difficulty of supplying power for pumps or compressed air for injection at points far from shore, and the problems associated with installing diffusers or other equipment in deep water.

Environmental Effects. Environmental effects that may arise include noise from compressors or gasoline-engine driven pumps, and possibly visual pollution from rising bubble plumes or floating aeration equipment. Any floating equipment must be cordoned off from the general public with barriers. The barriers, along with the equipment, will also have negative visual impacts.

The water quality of the reservoir will be altered, and will be manifested through various chemical and biological processes. Fish distribution will change along with their habitat (Ref. 6-71). A large part of this habitat evolves from the algal biomass, which can be both nutrient-limited and light-limited (Ref. 6-72). With destra-

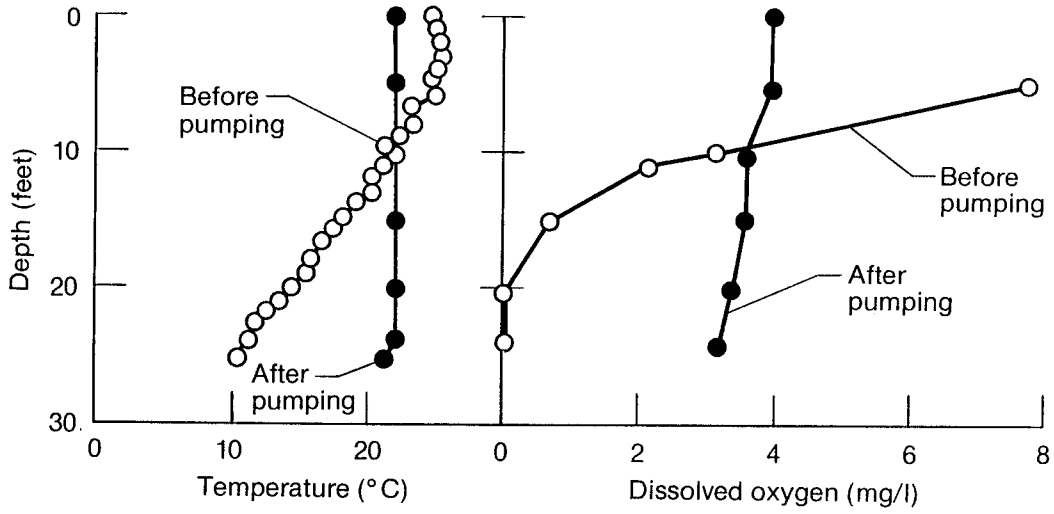


Figure 6-35. Temperature and oxygen changes due to mechanical destratification at Stewart Hollow Lake (Ref. 6-69).

tification, or the prevention of stratification, the balance of the algal production will shift, affecting such basic parameters as water clarity. Generally, phytoplankton numbers decrease (Ref. 6-73), but this is not always the case (Ref. 6-74 and 6-73). A method of predicting the change in biomass is provided by Lorenzen and Mitchell (Ref. 6-75).

Equipment Life Expectancy. Destratification equipment consists of either mechanical pumping systems or compressed air devices. Both types of equipment require regular maintenance, but properly installed equipment should be expected to last 20- to 30-years, particularly since it is in service only a portion of the year.

Safety. Normal precautions must be taken for any system with operating equipment such as compressors or pumps. Additional efforts should be made to protect the public, particularly when floating mechanisms are part of the design.

Possible Modes of Failure. Previous applications have experienced mechanical breakdowns with pumps and compressors, and broken supply lines. The majority of these occurred in applications during the 1960s. Improved materials used in today's applications should lessen the risk of mechanical failure. In addition to mechanical failure, system design parameters are such that failure due to undersizing is common (Ref. 6-76).

Risk Analysis. Based upon the success of others, the risk associated with the destratification of smaller impoundments must be considered small, particularly because the capital outlay to install a system is generally less than other aeration techniques. Should the initial system not perform as well as expected, it is neither difficult nor expensive to expand it.

Larger reservoirs require larger expenditures, particularly if the entire reservoir is to be completely destratified. Even though existing data is favorable, until additional applications have been made, the risk for larger applications is relatively high. The reported success of the Australians, however, is encouraging, and further research in this area is advocated.

Sizing. Due to a greater number of applications, the ease of installation, simplicity of use, and larger database to draw upon, this discussion will only concern itself with the air-injection type of destratification system.

A guide to sizing destratification systems is presented by Lorenzen and Fast (Ref. 6-77), and the process is basically built upon the fact that previous installations indicate that a general air injection rate of 30 SCFM is required per 10^6 square feet of reservoir surface area to achieve good mixing. Using this figure, the process of designing a system is similar to that of any submerged diffuser aeration technique. Johnson's method (Ref. 6-90) also takes into account reservoir depth and reservoir oxygen demand.

Several points to remember when designing a destratification system are:

- Mixing will only occur above the level of air injection.
- It is preferable to orient the diffuser system parallel to the dam, perpendicular to the flow.
- Because rising plumes of bubbles spread horizontally at a nominal rate of 0.05-ft/ft of rise, orifice spacing should minimally be 0.1 times the depth of air release. For example, if the rise height of the bubbles is 80-feet, the diffusers should be at least 8-feet apart.

Knowing the required air flow rate, the design process requires calculating the number of diffusers, sizing the diameter of the supply line, determining pressure losses through the system, and sizing the compressors. The reader is referred to the Working Example of Section 6.1, Tailrace Aeration Techniques / Submerged Diffusers for additional details regarding the procedure for sizing supply lines and compressors.

Working Example:

Assumed conditions:

Surface area of reservoir: 1,000 acres
Depth of diffusers: 70-feet
Distance from diffusers to compressors: 300-feet
Operating air temperature: 20°C

If 30 SCFM of air is required per 10^6 square feet of surface area, a total of 1,000 * 43,560 ÷ 10^6 * 30 = 1,307 SCFM will be required. Using flexible membrane diffusers 13-inches in diameter at a flow rate of 6.6 CFM each, approximately 200 diffusers will be required. If the diffusers are to be 7.0-feet center to center, the total length of diffusers is 1,400-feet. If diffusers are arranged in 2 parallel rows, each row would be 700-feet long.

To size the compressor, the pressure acting on the diffusers is 70-feet (30.3 PSIG), and, assuming a 5% pressure loss in the system, the total supply pressure must be approximately 75 PSIG (90 PSIA). Using Table G-2 (Appendix G) approximately 160-hp will be required. To provided system backup and a degree of staging to meet various demand conditions, two 150-HP compressors would be used in this case, each supplying 650 CFM of air at 75 PSIG. With the 5% frictional pressure loss, the supply line would only need to be 1-inch in diameter.

Costs. The cost of the destratification system will be composed of both initial installation costs, plus annual operational and maintenance costs. Because the diffusers are simply attached to two long headers and submerged, installation is considerably easier than if racks were used. For the Working Example, the installed cost of the diffusers is estimated to be $150 each, for a total of $30,000. From Figure 6-11, a two-stage rotary vane compressor would be appropriate. Table 6-3 indicates the approximate installed cost of the compressors to be $40,000. The total installation cost is estimated to be:

Diffusers, installed:	$30,000
Compressors, installed:	40,000
Subtotal:	$70,000
Engineering:	7,000
Total installed cost:	$77,000

Annual costs would include energy for the compressors, maintenance, insurance, and labor. If the system operates continuously for a 6-

month period[10], the energy costs of 160-hp (96 kW) is: 96 kW x 24 hr/day x 30 days/mo x 6 mo x $0.06/kW = $24,883. Annual maintenance is valued at $9/horsepower for compressors used year-round in industrial applications (Ingersoll Rand book). For this example, the units are used 6-months of the year, so the cost will be assumed to be $4.50/horsepower. The total annual maintenance is estimated to be approximately $720.

There will also be a labor cost required to operate the compressors. Assuming one man is required 8-hours/day when the system is running, the annual cost would be $36,500. The total annual costs are estimated to be:

Energy:	$24,883
Insurance (1/30th installation):	2,333
Maintenance:	720
Labor:	36,500
Total annual costs:	$64,436

The Present Worth of a 30-year series of annual payments of $64,436 each is $519,032 at 12% interest.

The total Present Worth of a reservoir destratification system is estimated to be:

Initial installation:	$ 77,000
Annual cost (Present Worth):	519,032
Total Present Worth:	$596,032

($73,995 per annum for 30-years at 12%).

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[10]As discussed, the Australian installations indicate that intermittent operation is considerably less costly than continuous operation. As more information becomes available, this should be considered in the cost estimate.

Case Study. One of the longest and most intense efforts at reservoir destratification using air injection has been Casitas Reservoir in southern California. The reservoir has a maximum depth of 269-feet, a surface area of approximately 2,700 acres, a shoreline of 32-miles, and contains 254,000 acre-ft of water. Due to poor water quality, an air-injection destratification system was installed in 1968, and has operated (with modifications) every year since.

The air supply is provided by two 75-hp electric motor driven, single stage positive displacement compressors, each designed to provide 315 CFM at 100 PSIG. When the system is operating (early April through mid-October), the compressors run continuously. The air is routed to the diffusers via 1,700-feet of 3-inch diameter Schedule 40 steel supply pipe, suspended in the reservoir 1-foot below the surface with floats. Originally, the supply pipe split into two main headers, each 105-feet long, 3-inches in diameter. Four 180-foot, 1-inch diameter high pressure air hoses were located along each header at 70-foot intervals, and each hose was attached to a fabricated diffuser. Air was injected at depths ranging from 130-feet to 180-feet.

The diffusers consisted of 4-inch diameter steel pipe, 10-feet long, filled with approximately 9-feet of concrete. The pipe was sealed at both ends with welded steel plate. The supply hose was attached to the end plate with the 1-foot cavity, where air was diffused through nine 3/16-inch holes.

Even though only 630 CFM were being injected[11], total destratification was not accomplished. Mixing occurred, however, in all parts of the reservoir, and reservoir DO levels improved considerably. Prior to injection, water at levels below 20-feet in depth regularly became anaerobic, and on the average, water with 4 mg/L DO was only located in the upper 30-feet of the reservoir. Once the system became operational, DO levels began to gradually improve, year by year. By 1974, oxygen was present year-round at all levels above 120-feet, and anoxic conditions only existed at depths greater than 160-feet for a

[11]Based on 30 SCFM/10^6 square feet, the recommended air delivery rate for Casitas Reservoir is more than 3,500 CFM.

period of less than 6-weeks each year. The upper 80-feet of the reservoir averaged 4 mg/L DO or greater. (Ref. 6-78)

In 1976, new diffusers were installed. Using the same supply system, seven 2-inch diameter PVC pipes, 100-feet long, were submerged to a depth of 150-feet and connected to the main supply header with 1-inch diameter hoses. Holes (1/32-inch diameter) were drilled on 1-foot centers in each pipe. This configuration has reduced air and power demands by 50%, and has resulted in the upper 150-feet of the reservoir to average 4 mg/L DO, or greater. (Ref. 6-79)

Hypolimnion Aeration

If the reservoir under consideration is large (> 3,000 acres), or temperature increases in the discharge are undesirable, destratification techniques may be too costly or simply unsuitable. Hypolimnion aeration, however, is an alternative reservoir technique that has been studied and applied for a number of years to improve the water quality of lakes and reservoirs (Ref. 6-80 and 6-81). In one of the more ambitious projects, the Corps of Engineers (COE) has applied the technology to improve the DO content of the discharge from Richard B. Russell Dam in Georgia.

Physical Aspects. Although many ingenious devices have been conceived and developed to aerate the hypolimnion without affecting other levels of the reservoir (Ref. 6-81), the least complicated to apply and design thus far is that which the COE used at Richard B. Russell. With the recent refinements in diffuser hardware, namely flexible membranes, and the ever increasing base of knowledge accompanying hypolimnion aeration, pure oxygen injection has evolved as one of the most practical techniques.

In its simplest form, a pure oxygen system will consist of a leased LOX storage site complete with tanks and vaporizers, connected to two or three supply headers submerged and anchored in the reservoir, well upstream of the dam (Figure 6-36). Flexible membrane diffusers mounted directly on the supply headers would be used to optimize absorption efficiency and minimize maintenance.

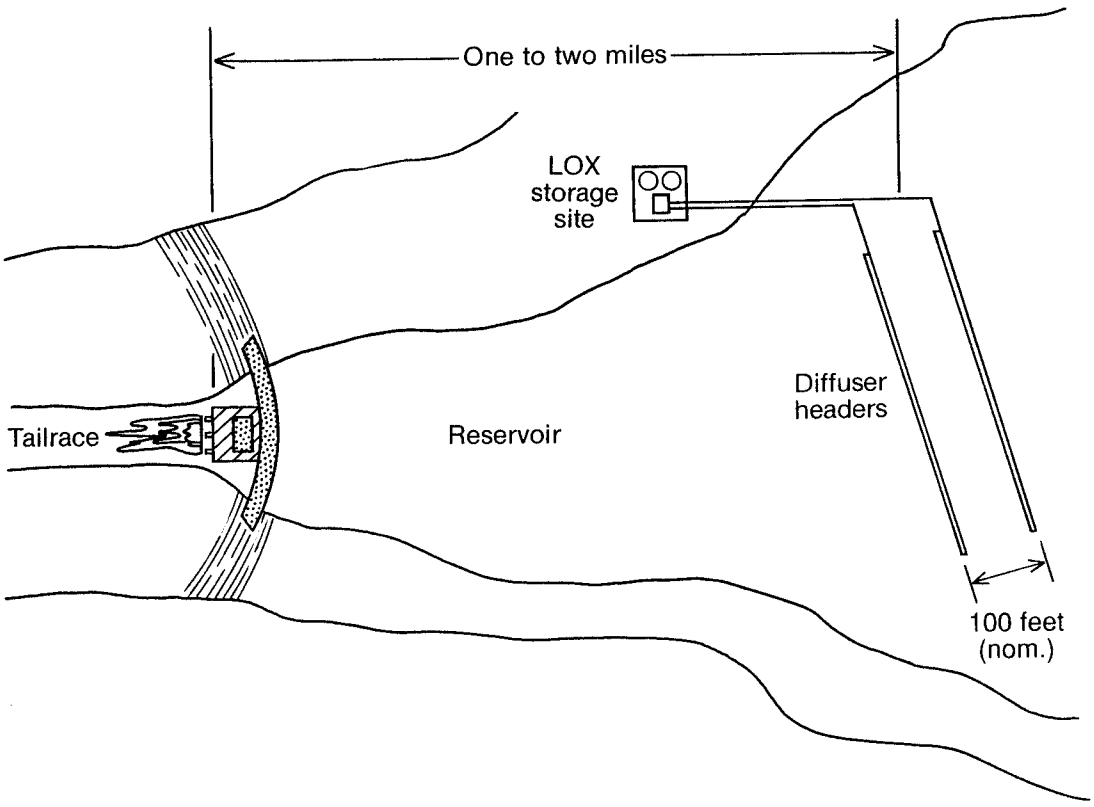


Figure 6-36. Typical Reservoir/Hypolimnion Aeration System Located Well Upsteam of Dam.

Working Principles. The overall concept of hypolimnion aeration, and more specifically hypolimnion pure oxygen injection, is to take advantage of the depth to increase transfer efficiency, and to utilize the reservoir volume to store the DO prior to discharge through the turbines. By utilizing the volume of the hypolimnion for storage of aerated water, not only can the injection system be downsized from one designed to meet the immediate needs of peak-power generation flow, but considerable savings can be made in equipment if on-site oxygen generation is also part of the overall installation.

Limitations, Constraints, and Trade-Offs. Although the system is ideal from a peaking-power viewpoint, this technique imposes a limitation when conditions are such to allow for continuous power generation. If the injection system is located far enough upstream to provide enough aerated water to meet the peak-power demand for one or two days, the reserve of aerated water will be quickly depleted if the generators are operated 24-hours per day. If such a situation is likely, additional aeration equipment would be required to meet the occasional continuous generation demand. The additional equipment could be located in the vicinity of the original system, or, as in the case of Richard B. Russell, in the forebay area of the dam.

One additional limitation is generally imposed due to the large volumes of required oxygen and the depth of injection. Supersaturation of dissolved nitrogen is likely to be a problem if air is used as the oxygen source. Therefore, the systems are usually limited to injecting pure oxygen.

Major Obstacles to Installation. As discussed in the previous paragraph, if two aeration systems are used (one located well upstream of the dam and one in the forebay), the major obstacle to installation would be siting the LOX storage facility. Either two sites could be located separately, one serving each system, or a single LOX site could serve both systems using a long supply line. In either case, the additional costs may become prohibitive.

Because the main injection system will be located some distance from the powerhouse, consideration should be given for remote operation, safety, and vandalism.

An advantage of injecting oxygen far above the dam is that the diffusers can be mounted directly to the supply header. Installation is somewhat easier than for the case of gas injection in the forebay, where the diffusers must be clustered about the turbine intake structure.

Environmental Effects. Adverse environmental effects are linked to the system's source of oxygen. If a LOX system is replaced with an on-site oxygen generation plant, both visual and audible environmental effects must be considered. Because the diffuser system is located on the bottom of the reservoir, it has very little negative impact environmentally, but many positive effects on the water quality of the entire reservoir.

Equipment Life Expectancy. Based on experience from wastewater treatment applications, flexible membrane diffusers last 2- to 6-years. For reservoir applications operated approximately 6-months of the year, the diffusers should last 10-years or more before membrane replacement becomes necessary. The distribution piping system, if properly designed and constructed, will last considerably longer than the diffusers; 30-years would be an estimate based upon the limited applications of this type.

If a LOX system is used to supply oxygen, it is recommended that the equipment be leased from the supplier, thereby relieving the owner of the responsibility of maintenance. If an on-site oxygen generation plant is part of the design (see Appendix G), equipment life will depend upon the annual number of hours of operation and the maintenance provided. The critical components of these systems are the compressors. With good maintenance, they should last the life of the system (30-years) (Ref. 6-18).

Safety. The normal safety hazards associated with the use pure oxygen are discussed in Appendix G, and accompany any oxygen system. Additional precautions will be necessary while installing and maintaining the diffusers. A safety benefit of a system located far upstream is that the possible fire hazards are also removed from the powerhouse. However, the risk of vandalism may outweigh this advantage.

Modes of Failure. Modes of failure can include an interruption of the oxygen supply to the system, a rupture of an oxygen supply line, or possibly clogged diffusers. If the system is poorly designed, the flow rate to diffusers and/or the number of diffusers may be inadequate to meet the oxygen deficit. An advantage of this technique, however, is that additional diffusers can be added or taken off-line as demand dictates.

Risk Analysis. Because the working principles are straightforward and relatively well proven, the chances of this option performing as expected is high. Additionally, this option has an inherent flexibility that allows it to be expanded or relocated at relatively minor expense.

Sizing. Design procedures for hypolimnetic aeration systems are presented by Speece (Ref. 6-82), Ashley (Ref. 6-83), and Lorenzen and Fast (Ref. 6-84). However, for initial estimating purposes involved in technique comparisons, the sizing of a basic system to meet the needs of a peaking-power operation is relatively simple. A transfer efficiency must be assumed based upon the depth of the diffusers and the results of other installations, and a daily oxygen demand must be determined based upon the reservoir's internal DO demand and facility operations. Detailed, final designs must include the oxygen demand imposed by the hypolimnion itself, as discussed by Lorenzen and Fast (Ref. 6-84) and Ashley (Ref. 6-83).

Working Example:

Assumed conditions:

Generation flow:	2,700 CFS
Daily operation:	6-hours/day
Initial DO content:	0.0 mg/L
Desired DO level of discharge:	4.0 mg/L
Water temperature of hypolimnion:	12°C
Reservoir depth at injection location:	100-feet
Depth of epilimnion:	25-feet
Volume of hypolimnion downstream of injection location:	52,800 acre-ft

With a generation flow of 2,700 CFS, operating 6-hours/day, and a deficit of 4.0 mg/L, the daily oxygen demand due to the generation flow would be:

$$2{,}700\ ft^3/sec * 3{,}600\ sec/hr * 6\ hrs/day * 28.32\ L/ft^3 * 4\ mg/L / (9.08 \times 10^8)\ mg/ton = 7.3\ tons/day$$

If the daily hypolimnetic oxygen demand is assumed to be 0.1 mg/L, the total oxygen required to meet this demand is:

$$52{,}800\ acre\text{-}ft * 43{,}560\ ft^3/acre\text{-}ft * 28.32\ L/ft^3 * 0.1\ mg/L / (9.08 \times 10^8)\ mg/ton = 7.2\ tons/day$$

Thus, the total demand is (7.3 + 7.2) = 14.5 tons/day.

Based upon other installations (Ref. 6-39 and 6-40), a conservative absorption efficiency of 75% shall be assumed for diffusers located at a depth of 95-feet. This would require that 14.5 / 0.75 = 19.3 tons per day be injected. Because oxygen has a density of 0.08279 lbs/ft^3 at 70°F, 324 CFM must be continually injected for each day of power generation.

Using 13-inch diameter flexible membrane diffusers at a delivery rate of 6.6 CFM each, a total of 50 diffusers are needed. Because bubbles in rising plumes travel horizontally at a rate of 0.05 ft/sec (Ref. 6-84), diffusers should be spaced 0.1 ft times the depth of injection, or, in this case, 9.5-feet center-to-center, minimally. This would require a single supply header to be approximately 500-feet long.

To complete the installation estimate, the pressure at the point of injection is approximately 41 PSIG. Assuming a supply pressure of 45 PSIG and a frictional piping loss of 2 PSI, Appendix G indicates that the supply header should be 3-inches in diameter.

Costs. The cost of the Working Example can be broken down into initial installation and annual costs. Initial installation of the system is straightforward. A site must be prepared for LOX storage, and the header must be assembled and installed. In this case, the cost of the header hardware is approximately $85/diffuser, and installation is an additional $6,000, totalling $10,250. Site work for the LOX site would consist of grading, building a foundation, an

access road, and security fencing. The approximate cost for this work is $25,000. The total installed cost is:

Diffuser hardware:	$4,250
Installation:	6,000
LOX site work:	25,000
Subtotal:	$35,250
Engineering:	3,525
Total installed cost:	$38,775

Annual costs include oxygen (19.3 tons/day at $75/ton), insurance, rental of LOX equipment, and labor (estimated at 1-hour/day when the system is operating). If the system operates 5-months of the year, the annual costs are estimated to be:

Oxygen:	$217,125
Insurance:	1,175
LOX rental ($1,300/month):	15,600
Labor:	3,750
Total annual costs:	$237,650

A series of annual payments of $237,650 for a period of 30-years has an equivalent Present Worth of $1,914,271 at 12% interest.

The total Present Worth of an upstream hypolimnetic oxygen injection system is:

Initial installation:	$38,775
Annual cost (Present Worth):	1,914,271
Total Present Worth:	$1,953,046

($242,451 per annum for 30-years at 12%).

It should be pointed out that the above cost is for a continuous injection system; it does not include the cost of an auxiliary system to meet continuous generation needs. However, examining the individual expenses, the large majority of the cost is in the annual expense for oxygen. The cost of expanding the system hardware to allow for continuous generation would be relatively small.

It should also be noted that, because the greatest single cost expenditure is for oxygen, accurately estimating the hypolimnetic oxygen demand is very crucial. In the last example, the assumed hypolimnetic demand represented 50% of the oxygen load and expense. Actual field measurements to determine this variable should be made to more accurately estimate these costs.

Case Study. The Corps of Engineer's installation at Richard B. Russell Dam in Georgia is probably the best example of upstream hypolimnetic oxygen injection applied for the improvement of tailwater DO levels. The project has been described in a number of publications (Ref. 6-85, 6-86 and 6-40), and is summarized here.

Richard B. Russell Dam is a large installation, 195-feet high and 1,900-feet long, flanked by two earth embankments. The powerhouse will eventually house 600 MW of power, with a maximum release of approximately 60,000 CFS. However, half of the eight generators will be pumped storage units, returning 30,000 CFS to the reservoir. The J. Strom Thurmond Dam and Reservoir (formerly Clarks Hill Dam and Lake) are located 37-miles downstream of the dam, and Hartwell Dam is 30-miles upstream. Richard B. Russell Lake was first impounded in 1984.

Prior to impoundment, the Corps conducted several oxygen injection experiments in Clarks Hill Lake. The work evaluated various diffuser efficiencies and injection techniques, and is invaluable information when sizing similar installations at other sites. The investigative work led to the design of the present oxygen injection system in Richard B. Russell Lake. The system consists of continuous-injection diffusers located 1-mile upstream of the dam, and a "pulsing" injection system located immediately in front of the intakes. Overall, the design has allowed for a maximum injection rate of 150 tons/day.

The continuous system consists of a distribution pipe from the LOX facility to two parallel diffuser pipes suspended 5-feet above the lake bottom, approximately 130-feet below the surface. The two diffuser pipes are approximately 1,600-feet long and are spaced 100-feet apart. For the pulsed system, a main supply line is routed from the LOX facility to the top of the dam. Eight lines branch from the

top of the dam, run down the face, and connect to the diffuser lines located between and perpendicular to each intake. The diffuser lines consist of an 8-inch diameter center manifold made from fiberglass reinforced plastic pipe. Floats are attached to the pipe to provide a constant positive buoyancy to the system during shutdown (Figure 6-37). Vertical and horizontal alignment of the system is accomplished with stainless steel cables connected to concrete blocks on the bottom of the reservoir. Flanged to the manifold are sections of 4-inch Schedule 80 PVC pipe, 20-feet in length. The 7-inch diameter, silica glass diffusers are spaced 1-foot apart on the pipe. The diffusers have a standard permeability of 2 ft/min.

The cost of the system in 1984 was $3.9 million, not including engineering. The $3.9 million included $1 million for the LOX equipment and $2.9 million for the diffuser and distribution piping system. Adjusting for inflation, the $2.9 million dollars would be roughly equivalent to $3.2 million in 1989. Using Means Mechanical Cost Data for 1989 (Ref. 6-12), the approximate installed cost of the 2-mile supply line connecting the dam and the LOX site is $2.6 million. Thus, the cost of the 3,888 diffusers used at Richard B. Russell in 1989 dollars is approximately $154 each. Considering that the silica diffusers are approximately twice the price of the flexible membrane type, this figure is in close agreement with today's estimated cost of installing diffusers in reservoirs.

Over the first several years of operation, the system at Richard B. Russell has been able to supply the downstream fisheries with water above 6 mg/L. Reservoir DO profiles taken both upstream and downstream of the reservoir aeration system are illustrated in Figure 6-38. Gas analyses of the bubbles have shown bubble size greatly influences oxygen transfer efficiency. Measured efficiencies have ranged from 20% to 96%, with smaller bubbles averaging greater than 80%, and larger bubbles averaging less than 50%. The dissolved oxygen levels released from the dam reflect an overall transfer efficiency greater than 75%.

Recent problems concerning the project involve fouling of the silica glass diffusers. Although a cleaning procedure was recommended on a yearly basis, it apparently was not conducted regularly. Fouling of

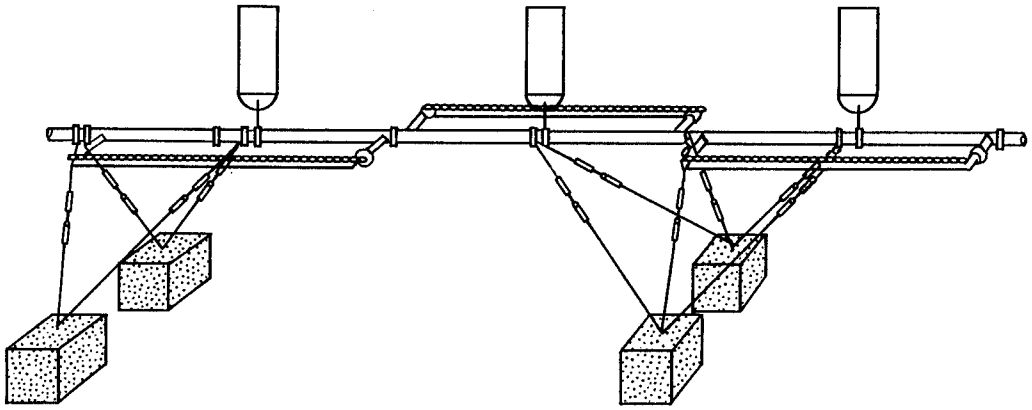


Figure 6-37. Typical section of Richard B. Russell diffuser piping (Ref. 6-86).

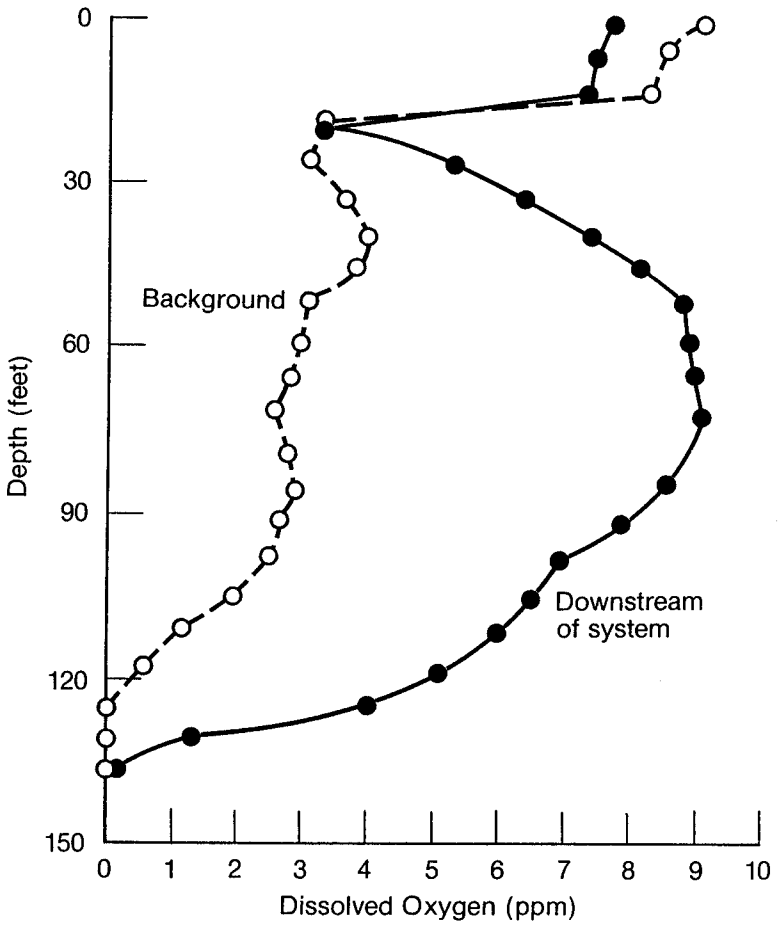


Figure 6-38. In-lake DO profiles upstream and downstream of continuous oxygen injection system at Richard B. Russell installation (Ref. 6-86).

the diffusers has resulted, and different measures were being taken to correct the problem, including cleaning with hydrogen chloride gas. Replacement with flexible membrane-type diffusers is also being considered.

6.4 OPERATIONAL TECHNIQUES

The simplest approach to meeting DO standards is categorized as Operational Techniques. Without the addition of auxiliary equipment, downstream DO levels are enhanced to meet imposed standards by blending generation flows with auxiliary flows released over the spillway or through bypass valves. Optionally, it may also be feasible to schedule generating periods based upon the diurnal variations of DO in the reservoir, producing power only when the DO level will meet the standard. As discussed below, however, a considerable sacrifice of water and power generation is made for the simplicity of this approach.

Spilling Water for Aeration

Physical Aspects. Spilling of water for aeration can be accomplished in a number of ways, all of which must result in the spilled water being at or near saturation when it is mixed with generation flows. "Spilled" water may be released over the spillway, or released via bypass valves that consequently aerate the water as the energy is dissipated. Control gates must be used for water released over the spillway.

Working Principles. In technical terms, a mass balance is used to determine the required spilled flow, based upon the DO level of the generated flow and the imposed standard. The equation used to determine the volume of the spilled flow is:

$$Q_{SP} = Q_{GN} \times \frac{(DO_{MIX} - DO_{GN})}{(DO_{SP} - DO_{MIX})}$$

where:

Q_{SP}	=	Spilled flow (CFS)
Q_{GN}	=	Generator flow (CFS)
DO_{MIX}	=	DO content of mixed flow (mg/L)
DO_{SP}	=	DO content of spilled flow (mg/L)
DO_{GN}	=	DO content of generator flow (mg/L)

The DO content of the spilled water is a function of its temperature and the amount of aeration that takes place during release. If the spilled water is taken from the epilimnion, it will normally be near saturation initially. Any additional aeration that occurs during release helps assure that the water is at saturation when mixed with the generator flow. Appendix G tabulates various saturation levels versus temperature.

If an aeration valve is used to bypass water, such as a Howell-Bunger valve, the released water can again be considered saturated, particularly if the release is made to the atmosphere (above tailwater) (Ref. 6-87).

Thus, to determine the amount of spilled water, the final desired DO level of the discharge must be known, plus the DO levels of the both the generation flow and the spilled flow (normally assumed to be saturated).

Limitations, Constraints, Trade-Offs. If controlled releases cannot be made with existing equipment, spilling water to meet imposed DO standards will not be economically viable. The cost of retrofitting a facility to include control gates on spillways or to install aeration valves far exceed the costs of other options for aeration.

Two trade-offs are also likely to result in this technique being eliminated from consideration. As the Working Example will illustrate, the volumes of water needed to blend with generator flows are usually substantial, and may quickly deplete the reservoir's water resources. In addition, loss of power revenues due to spilled water are considerable. Other aeration techniques are generally far more economical.

Major Obstacles to Installation. If the equipment needed to spill water in a controlled manner is not pre-existing, the technique is usually uneconomical when compared to other approaches to aeration. As such, obstacles to installing the system do not apply to this technique.

Environmental Effects. Spilled flow will result in depleting the reservoirs water resource more quickly. This may mean lower surface water elevations, and possibly poorer water quality throughout the reservoir.

Downstream, water volumes will be increased, possibly affecting river uses during periods of generation.

Equipment Life Expectancy. Even in the case where control structures and/or bypass valves are in place, using the equipment to meet imposed DO standards will result in increased wear and a shorter service life. These costs must be included in the economic analysis if the technique is a viable option.

Safety. The major safety threat resulting from spilled water to meet imposed DO standards would be the increased downstream flows during periods of generation. Recreational users of the river could be threatened.

Possible Modes of Failure. Inadequate levels of dissolved oxygen could result from operator error if the spilled water was not released simultaneous to generation flow, or if the quantity released was not sufficient to raise the DO level of the blended flow to the required level. Equipment failure could also result in insufficient quantities of spilled water to be released. Finally, with the considerable quantities of water required, the water resources of the reservoir may become depleted, and the only flow allowed to pass downstream would be that to meet minimum release requirements.

Risk Analysis. The working principles of this technique are straightforward, and the risk in not providing the required DO level is very low. However, the economics are such that it is probably the least used method for meeting DO discharge standards.

Sizing. As discussed in the section dealing with Working Principles, sizing of a system is based upon the amount of spilled water needed to meet the imposed DO standard. In nearly all cases, the equipment must pre-exist for the technique to be economically viable.

To determine the equipment requirements, worst-case conditions are assumed, and the volume of spilled water needed to raise the generation flow to meet the DO standard is calculated. If the existing equipment cannot pass this volume of water at the time of year it is required, a new, larger installation must be designed and priced. Normally this renders the technique uneconomical.

If the existing equipment is capable of passing the flow, the cost associated with increased maintenance, lost power revenues, and operational labor must be calculated. The effect on the upstream reservoir and the downstream users must also be considered.

Finally, the impact of Replacement Generation Capacity must be considered. The release of spilled flows will certainly reduce the overall amount of power a hydro-facility can produce in a year, but may not affect the maximum generation capacity of the plant, unless the bypass flow is taken from the generation flow or the reservoir surface elevation is severely reduced. If the bypass flow is removed from the same penstock as that providing the generation flow, the capacity of the generator is reduced, and a cost for Replacement Generation Capacity must be considered.

Working Example:
Assumed Worst-Case Conditions:

Generator output:	22.5 MW
Generation flow:	2,700 CFS
DO content of generation flow:	0.0 mg/L
Reservoir surface water temp.:	24°C
Desired DO discharge level:	4.0 mg/L

It will also be assumed that the facility presently incorporates spillway gates that can be used to release and control the spilled flow. The spilled flow is saturated when it blends with the generation flow.

Using Appendix G, the DO content of the saturated spilled water is 8.4 mg/L. The mass balance equation can be used to determine the required spilled flow:

$$Q_{SP} = 2,700 * (4.0 - 0.0) / (8.4 - 4.0) = 2,455 \text{ CFS}$$

Thus, a flow nearly equal to that passing through the generator must be spilled to provide a DO discharge of 4.0 mg/L.

Costs. The first cost to consider when examining spillage aeration is the that of lost power generation revenues. Normally, this single cost will determine if more detailed effort should be put forth, or if other aeration options should be considered. To determine lost power generation revenues, the number of operating hours for a typical year must be known. These figures are normally available. However, detailed DO discharge levels and reservoir surface water temperature records are also needed. If they are not available, the designer must either perform field measurements over at least one season, or estimate the data from whatever existing records. By combining the facility's operating hours with the DO discharge and surface water temperature data, an estimate can be made as to the total annual volume of spilled water needed to meet the DO standard. By assuming an average head, this volume can be converted into an equivalent amount of power generated, and an approximate power revenue cost can be assigned. Even if the amount of available data is not large, the calculations can become involved, and it is recommended that either a spreadsheet or simple computer program be written to generate the final sum.

For the example, assume the facility operates 6-hours/day and that the average DO deficit of the generation flow and temperature of the reservoir surface water is as follows:

	DO	Temp.
Month 1:	1 mg/L	24°C
Month 2:	2 mg/L	26°C
Month 3:	4 mg/L	28°C
Month 4:	4 mg/L	28°C
Month 5:	2 mg/L	26°C

Under these conditions, the spillage flow would be:

	FLOW	MONTHLY TOTAL
Month 1:	2,455 CFS	36,521 ACRE-FT
Month 2:	2,634 CFS	39,183 ACRE-FT
Month 3:	2,842 CFS	42,278 ACRE-FT
Month 4:	2,842 CFS	42,278 ACRE-FT
Month 5:	2,634 CFS	39,183 ACRE-FT

The total water spilled over the 5-month period is 199,443 acre-ft. If the facility produces 22.5 MW at a flow of 2,700 CFS, the spilled water is equivalent to 894 hours of generation, or 20,115 MW-hours. At $0.06/kW-hr, or $60/MW-hr, the lost power generation revenues are $1,206,900 annually. Over a 30-year period, a series of payments this size would have a Present Worth value of $9,721,580 at 12%.

In nearly all cases, the lost power revenues alone are enough to consider the technique uneconomical, but a complete economic analysis would continue by estimating additional gate wear and labor. It should also be emphasized that the above cost assumes that the bypass mechanism is already in place, and that capital outlay for installation is not necessary.

Case Study. The only known example where spilling water proved to be economically viable is at Kingsley Dam on the North Platte River near Ogallala, Nebraska. Kingsley Dam is 162-feet high and 3.1 miles long. The maximum storage capacity of the reservoir is approximately 2-million acre-feet. Although the structure's primary purpose is the storage of irrigation water, a retrofit project completed in 1984 included a 50 MW generator. The facility incorporates two outlet structures: a seldom-used morning glory spillway 100-feet in diameter with a separate discharge shaft through the dam, and an Outlet Tower that releases water from the bottom of the reservoir through a ring gate. The water is directed via a penstock 19-feet in diameter to the Kaplan turbine. Branching from the penstock is a conduit 12-feet in diameter that is connected to a large Howell-Bunger valve, 9-feet in diameter. (Ref. 6-88)

With the initial operation of the powerplant in 1984, low DO levels in the tailrace were encountered. Extensive studies were performed,

examining all feasible approaches to enhancing the DO level. The results of the work indicated the most economical alternative would be to bypass a small amount of water through the Howell-Bunger valve during generating periods when the reservoir discharge DO level did not meet the imposed standard. The selection of using the Howell-Bunger valve would not have been feasible if the hardware had not been pre-existing as part of the facility. The estimated annual power generation loss is 5,206 MW-hours.

Part of the concern with using the valve is increased maintenance due to operation at low gate openings. Based upon the experiences of the Corps of Engineers and the USBR, operating Howell-Bunger valves at openings of 5- to 10-percent may cause additional cavitation damage, but operating at gate openings of less than 5-percent is likely to cause additional damage. This factor must be taken into account when considering Howell-Bunger valves for aeration purposes. The estimated range of openings to meet the imposed DO standard at Kingsley Dam is 3- to 10-percent.

6.5 COMBINATIONS OF TECHNIQUES

Imposed DO standards nearly always include an average daily level that must be maintained, plus an instantaneous minimum that can never be violated. Because the vast majority of hydroelectric plants operate for peak power generation, the DO standard can be used to the owner's advantage. During non-generating, off-peak hours, the small amount of minimum release flow can be aerated to a high level at relatively minor cost, and the much greater volume of generation flow need only be aerated to meet the minimum DO standard. This approach requires a combination of aeration systems: one to meet generation flows, and one to aerate the smaller minimum release flow.

Although aerating in this fashion will normally meet the standards, brief periods may exist when the aerated minimum release flow is too small, when averaged with the generation flow, to meet the standard's prescribed daily average. In this case, the generation flow must be aerated somewhat higher than the minimum to meet the daily average.

Generally, this additional aeration is less than 1 mg/L greater than the minimum standard.

Because it is conceivable that a facility may encounter a period of high flows, 24-hour per day periods of generation are possible. Under these conditions, the aeration system used to raise the DO level of the minimum release would not be used, and the generation aeration system must be sized to aerate the full generation flow to the standard's daily DO average. Keep in mind that the system must be sized to aerate the entire generation flow, resulting in higher initial installation costs, but it will seldom be operated at 100% capacity.

The final selection of a system to aerate generation flows depends heavily on the owner's prioritization of the costs of energy. The previous sections illustrated the magnitudes of these costs, as compared to other costs such as installation and annual operations. For example, turbine venting is a relatively inexpensive technique to install if the work takes place during normal yearly maintenance outages. However, the costs quickly escalate if lost power revenues are included for the life of the system. Pure oxygen injection is relatively inexpensive to install, but the annual purchase of LOX can be considerable. To avoid the expense of purchasing LOX, on-site generation may be considered, but again, the additional cost of operating electric motor-driven compressors must be reflected in annual energy costs. Frequently, too, the system most favored may not have the ability to meet the standard, even when operating at its maximum. This is particularly true for turbine venting systems. Thus, the best solution may be a combination of techniques, each operating when conditions dictate.

The following discussions pertain to various combinations of techniques among many that could be considered. The limitations, constraints, trade-offs, obstacles to installation, environmental concerns, equipment life expectancy, safety considerations, possible modes of failure, and procedures for cost estimating of all combinations remain essentially the same as if the systems were acting alone. However, the overall risk associated with the system failing

to meet DO standards is reduced because the systems serve to backup each other.

Oxygen Injection and Aspirating Surface Aerators

Physical Aspects. As illustrated in Figure 6-39, this combination involves diffuser racks submerged in the forebay, supplied with pure oxygen to meet generation flows, and surface aerators in the tailrace for minimum flow releases. Detailed descriptions of each system can be found in the discussions dealing with their individual applications.

Working Principles. One advantage of this combination is the minor amount of electrical energy required to operate the system. In addition, the electrical energy is only used during periods of non-generation, so it has no real effect on Replacement Generation Capacity.

The diffuser will inject pure oxygen into the generator flow, with transfer efficiency being enhanced by the depth of injection and the turbulence encountered in the turbine and draft tube. The surface aerators are only meant to aerate the minimum release flow. Since the minimum release may be made via the spillway or a separate aeration valve, the surface aerators may only be needed for leakage flow. The object of the surface aerators is to maximize the DO levels of the discharge during periods of non-generation.

Sizing. The forebay diffuser system must be sized to meet continuous generation flows; this method has been discussed previously. Sizing tailrace aeration equipment to meet minimum flow releases may be more difficult if the source of the minimum release is a combination of both leakage flow and flow passed intentionally over the spillway or through a bypass valve. If this is the case, the mass balance equation must be used to determine the amount of aeration required. It should be pointed out that a practical limit of aeration exists for minimum releases. Saturation of the release could be considered the limit, but the realities of enhancing DO levels with aeration equipment are such that providing the last 1 or 2 mg/L of oxygen when approaching saturation is both difficult and expensive. A practical upper limit for tailwater aeration is approximately 1.5 mg/L less

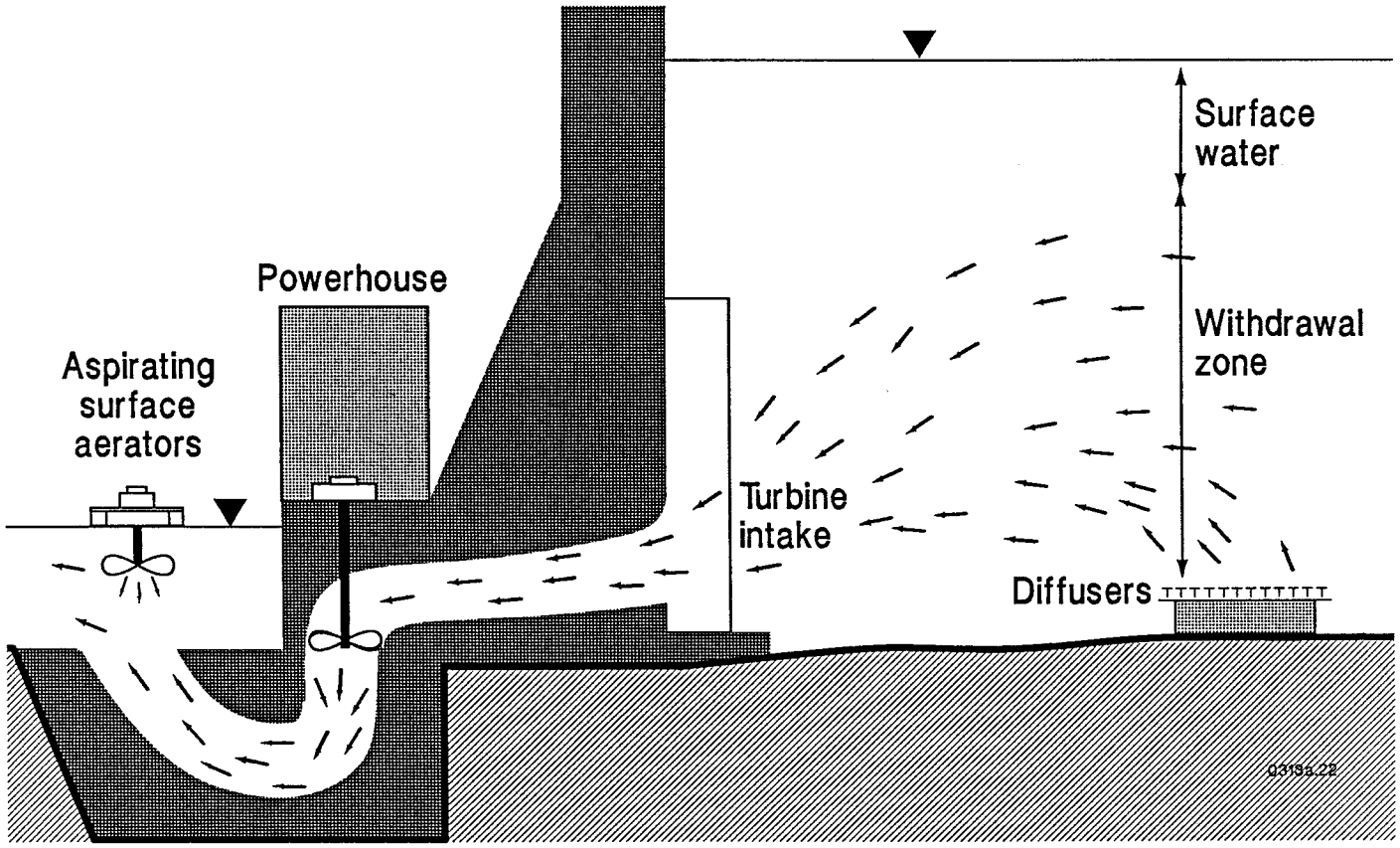


Figure 6-39. Oxygen Injection in Combination with Aspirating Surface Aerators.

than saturation. However, this should be verified with field measurements.

When sizing the tailrace aeration system DO contributions from the auxiliary bypass flow will aid in reducing the size requirements of the equipment, provided the auxiliary flow is at a high DO level. This would be the case if the flow was released over the spillway or discharged through an aeration valve. However, the aeration equipment should be sized based upon a "worst-case" condition. This would occur during drought conditions, when the minimum release is totally comprised of leakage flow, and no auxiliary releases are being made. The DO level of the leakage flow will probably be the same as that of the hypolimnion (i.e., near 0 mg/L in many cases).

Draft Tube Venting and Oxygen Injection

Physical Aspects. If energy and Replacement Generation Capacity costs are not of particular concern, draft tube venting is one of the more economical techniques. It involves relatively minor installation costs (again, ignoring the lost power revenues incurred during installation), and annual operational labor and maintenance costs are small. However, the technique is restricted by the amount of oxygen that can be injected in the short contact time that exists as the water travels through the draft tube. A possible means of augmenting the venting system would be to install a pure oxygen injection system in the forebay to provide a 1 or 2 mg/L increase in the incoming water, and to rely on the venting system to supply the remaining oxygen to meet the standard. This combination is illustrated in Figure 6-40.

Working Principles. Venting is most appropriate when DO deficits are no greater than 1 or 2 mg/L. If the initial incoming DO level is near zero, venting will normally not provide the entire aeration to meet the imposed standard. However, the transfer efficiency of pure oxygen injection systems improves considerably when the hypolimnion is nearly deplete of oxygen, and the desired increase is not great. If the desired increase is only 2 or 3 mg/L, and the initial DO level is near zero, transfer efficiency of a fine-bubble diffuser system located in water 80-feet deep should be 90% or greater. Combine this with a venting system that adds 2 mg/L, and nearly all minimum DO

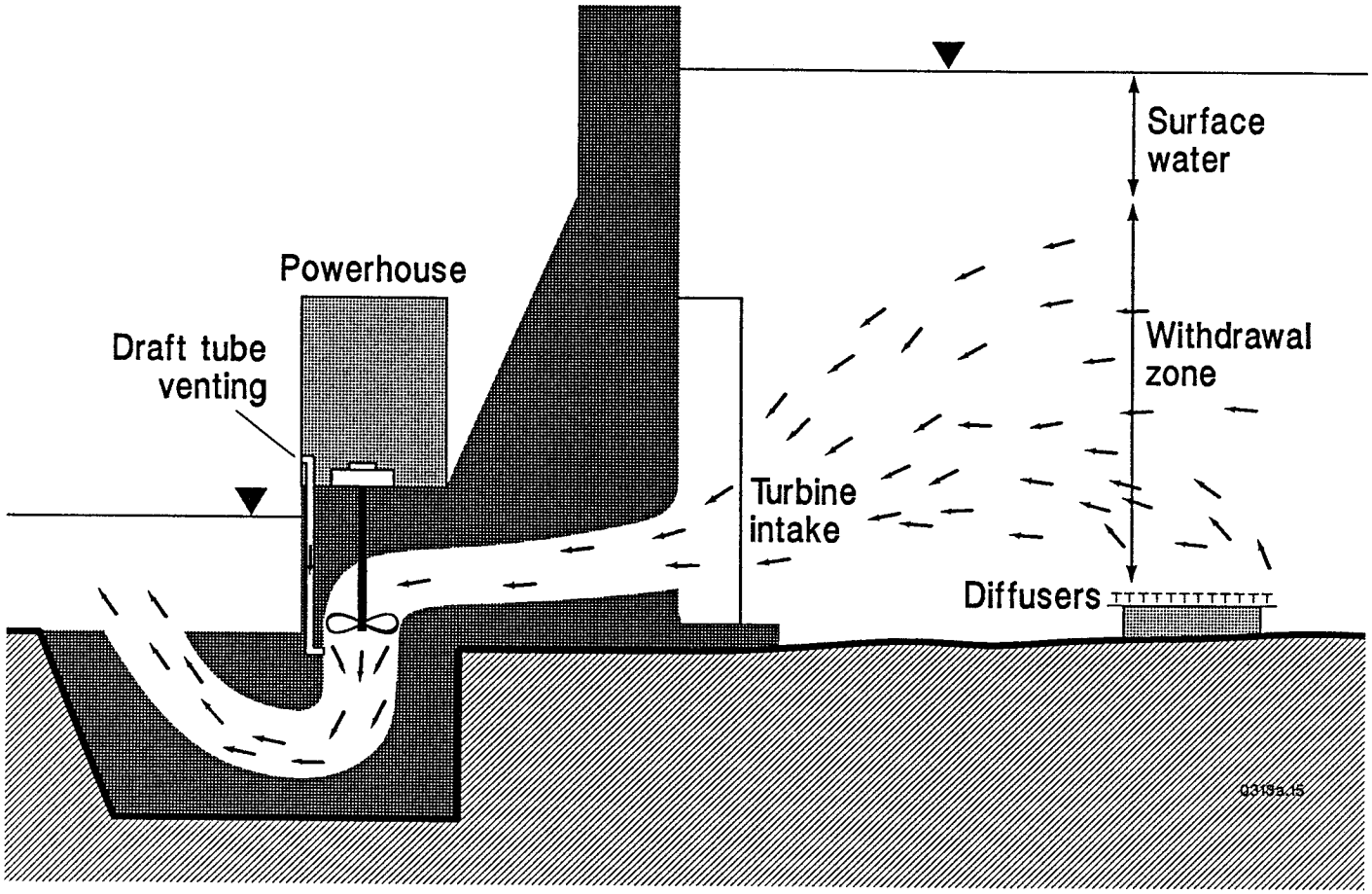


Figure 6-40. Oxygen Injection in Combination with Draft Tube Venting.

release standards will be met, if not all average DO release standards.

Sizing. Sizing of both the venting system and the diffuser system should be done as described in previous sections. The venting equipment should be sized for a 4% air flow, and a check should be made to assure that the site-specific conditions are correct for venting to occur. It may also be desirable to size the injection system to serve as a complete back-up to the turbine venting system.

Draft Tube Venting and Epilimnion Surface Water Pumps

Physical Aspects. When oxygen injection is not a desired alternative, epilimnion surface water pumps may be considered as a means of enhancing the discharge of a venting system. Figure 6-41 illustrates the combination. In actuality, each of these techniques may serve to enhance the other. The use of surface water pumps alone may be at risk due to the large volumes of epilimnetic water required to be blended with that from the hypolimnion. The venting system reduces the required volume. By combining the two techniques, the volume of epilimnion surface water is greatly reduced.

Working Principles. The aeration principles of both systems remain the same, helped by the fact that the required mass of DO to be supplied by the surface water pumps is considerably reduced.

Draft Tube Venting and Downstream Weirs

Physical Aspects. Once more depending upon site-specific circumstances, namely a low priority on the cost of energy and Replacement Generation Capacity, plus a site conducive to the construction of a weir, the combination of weirs and venting may be feasible (Figure 6-42).

Working Principles. In this case, a reduction in power generation will probably be incurred from both systems. The venting system should be capable of a 2 mg/L increase in DO levels, while the weir should add 3 to 5 mg/L. Both systems operating simultaneously could provide a 5 to 7 mg/L increase in DO.

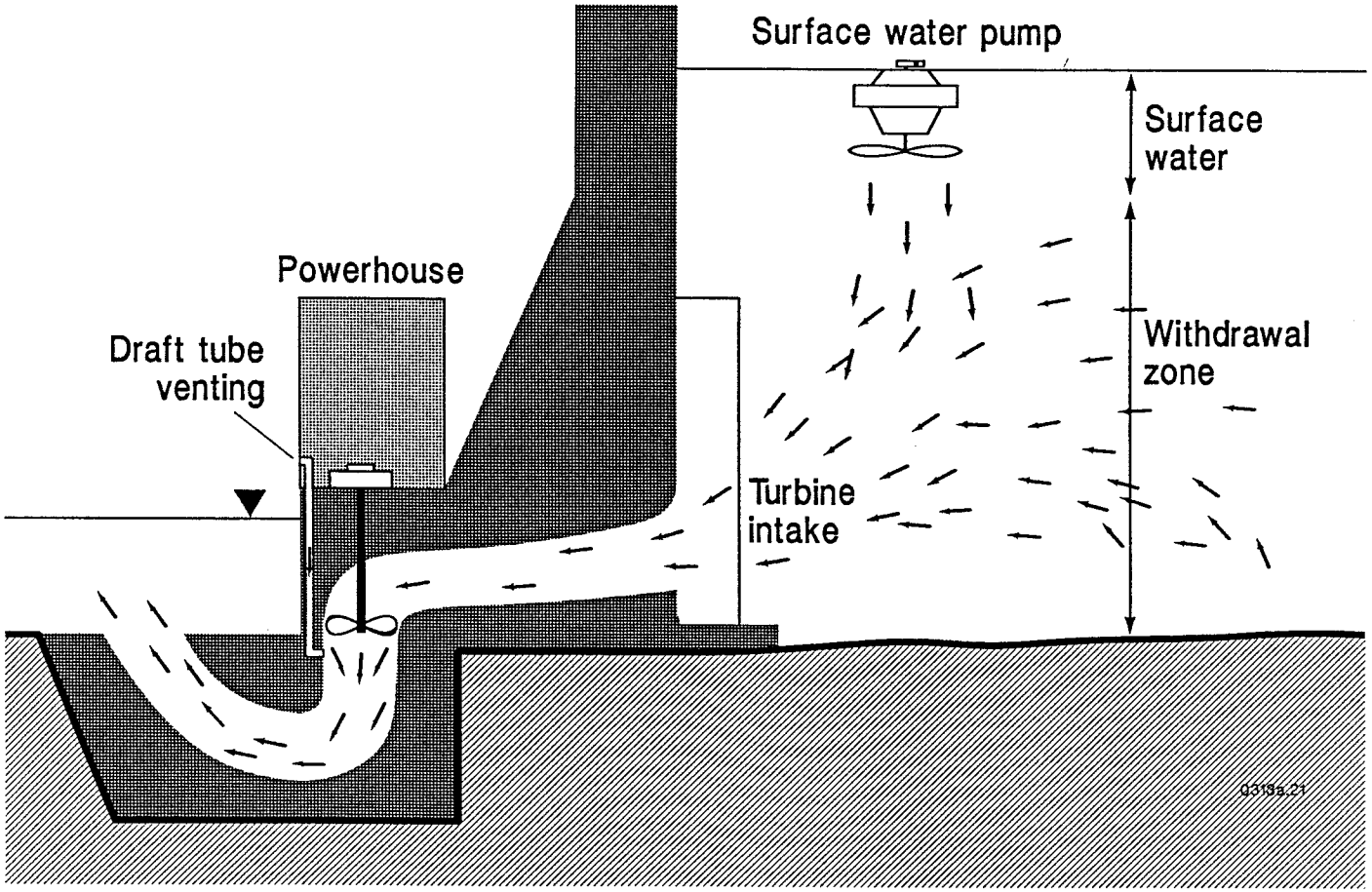


Figure 6-41. Epilimnion Surface Water Pumps in Combination with Draft Tube Venting.

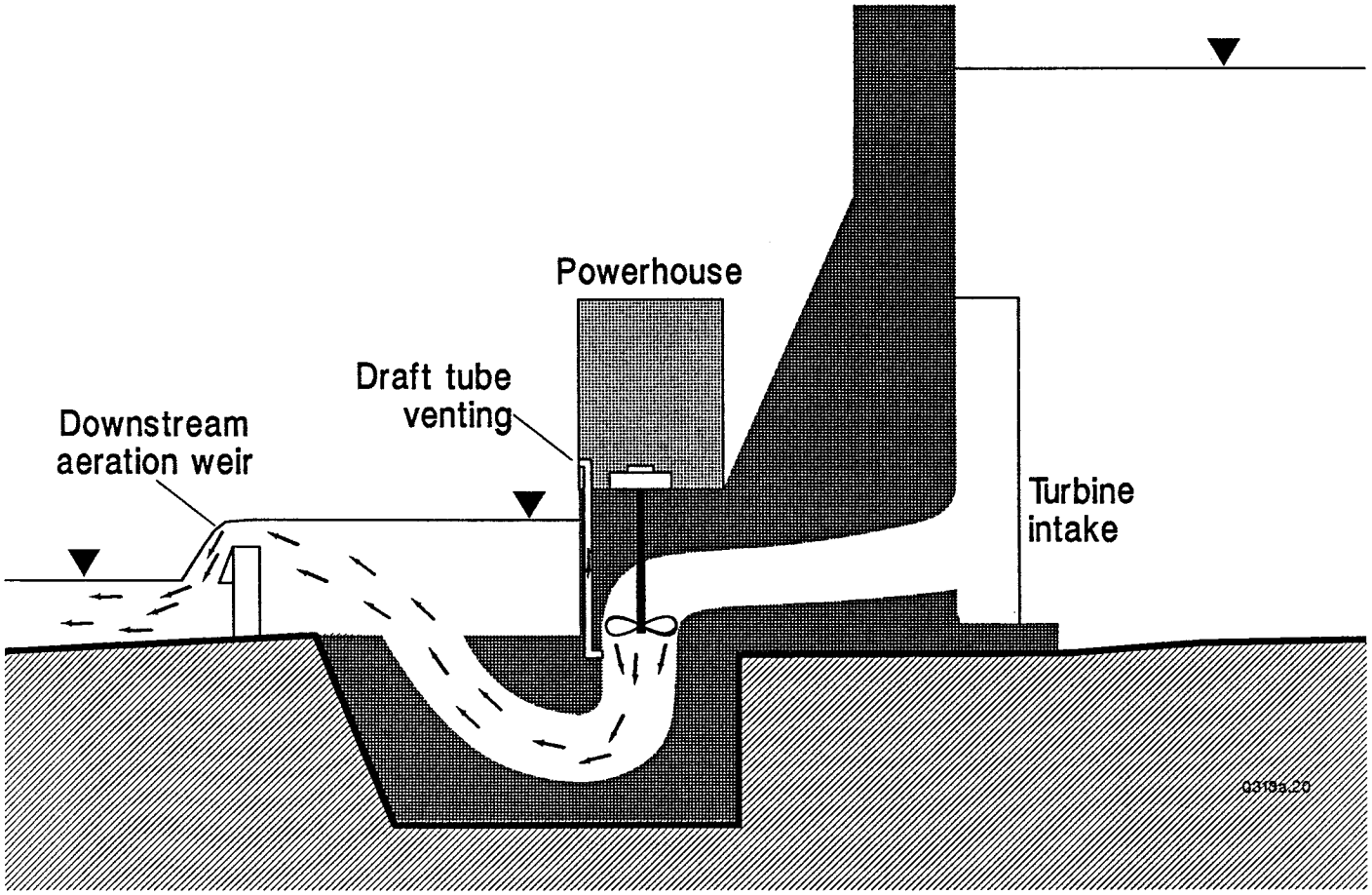


Figure 6-42. Downstream Aeration Weir in Combination with Draft Tube Venting.

If only a small increase in DO is required, the location of the weir and the induced headloss will dictate which system is most economical to operate. The venting system will typically result in a 2% power loss. In all likelihood, the weir will cause an effective headloss of 3- to 4-feet, or approximately a 3 to 4% reduction in generation if the effective head is 100-feet. In this case, the venting system would be operated as much as possible. If, however, the site is such that the weir can be located at a point far enough downstream so that the headloss no longer effects the turbine's discharge, the weir would be operated at all times, with the venting system used only to enhance the weirs performance when needed. In fact, if the weir could be located far enough downstream so as not to effect power generation, oxygen injection could be considered as an alternative to turbine venting to enhance the weir's performance, thereby eliminating the power losses incurred by the venting system.

6.6 TECHNIQUES UNDER DEVELOPMENT

Research, development, and testing of all techniques previously discussed continues to improve their performance with each application. However, another approach to aeration being considered for hydroelectric applications is that of sidestream injection. Although sidestream injection techniques have been successfully applied to other industries (wastewater treatment, aquaculture) for the specific purpose of increasing DO levels, they have not been applied on a scale comparable to hydroelectric discharges, and thus, are considered "experimental" or "developmental". They do, however, hold promise, particularly for run-of-river facilities. The overall working principle behind sidestream injection is a small portion of the main flow is diverted, treated under pressure to attain a very high level of DO saturation, and is subsequently returned to the main flow to provide overall enhanced DO levels.

Three types of sidestream injection techniques which could be applied to hydroelectric installations are presented below. They are U-Tube aeration, downflow bubble contactors, and a relatively new device called the Aquatector.

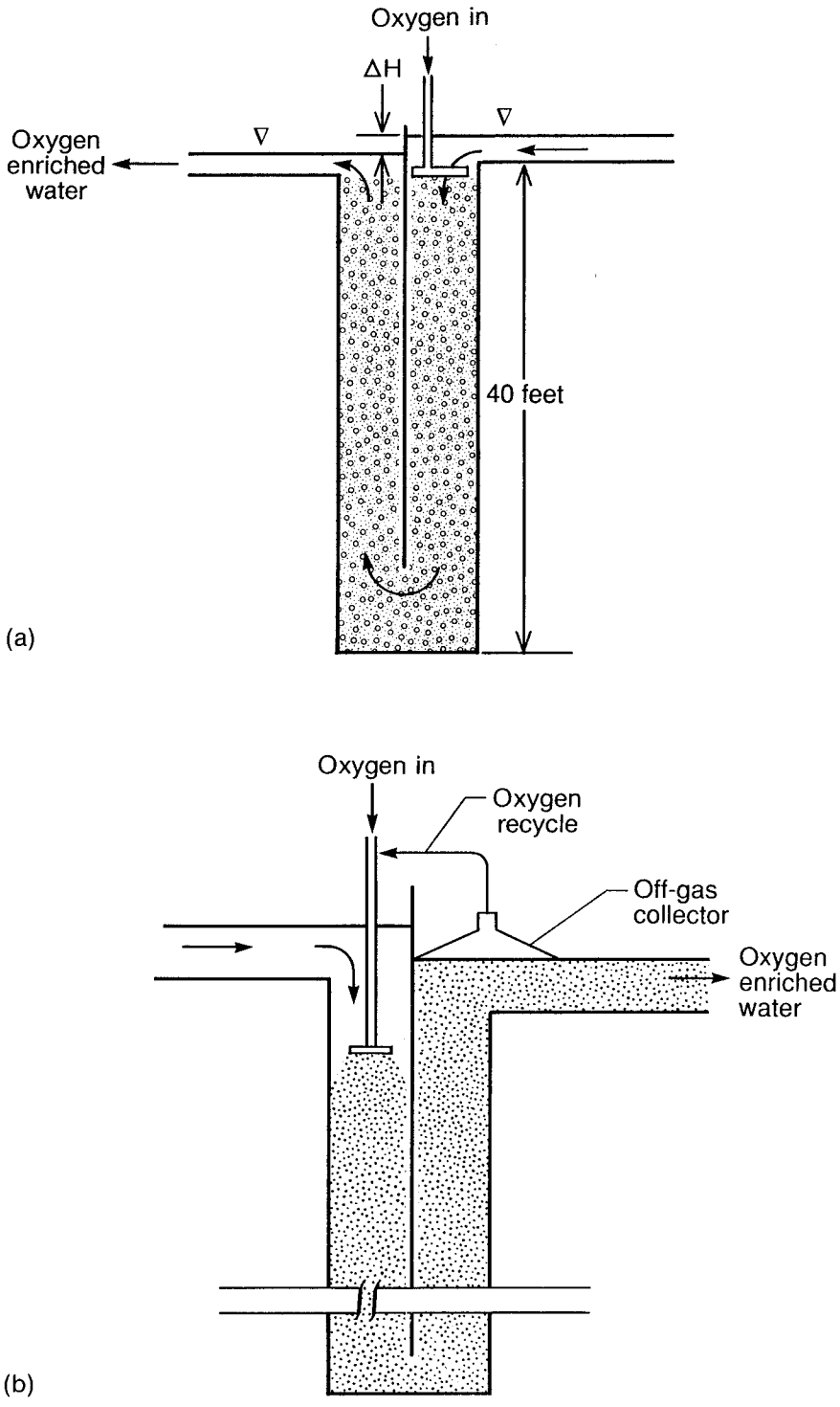
U-Tube Aeration

The name U-Tube is derived from the configuration of the waterflow, as illustrated in Figure 6-43. For large flows, a deep hole is constructed with a baffle inserted which extends from above the water surface to near the bottom of the hole. The waterflow is directed down one side of the baffle, underneath, and back to the surface. Air or pure oxygen is injected at the entrance.

The water velocity within the U-Tube is designed to exceed the buoyant velocity of the bubbles. The bubbles are carried down underneath the baffle and back to the surface. In the process, the hydrostatic head increases the DO saturation concentration and, thus, the driving force for gas transfer. The hydrostatic pressurization of the bubbles in the U-Tube makes it practical to produce DO concentrations in excess of 100% saturation at the discharge.

A U-Tube can function with either air or pure oxygen as the source of DO. However, pure oxygen is recommended for typical hydroelectric applications. Because pure oxygen is relatively insoluble in water, considerable care must be taken to insure efficient utilization. The U-Tube is particularly suited for efficient oxygen absorption because of the inherent characteristic of pressurization and prolonged bubble contact times. Oxygen absorption efficiencies of 90 percent can be achieved with a properly designed U-Tube.

In the design of U-Tube aeration systems, there are five parameters which can be varied independently (Ref. 6-89). These are: (1) gas-water ratio; (2) DO concentration in the inlet; (3) depth of U-Tube; (4) water velocity through the U-Tube; and (5) disperser depth. Previous systems indicate that minimum disperser depths result in maximum oxygen transfer economy. Assuming the inlet DO concentration is a fixed quantity, the designer selects a combination of the remaining variables to produce the desired DO concentration in the outlet. Each combination of variables will result in different capital and operating costs, and the combination which results in the lowest overall cost will be selected.



(Ref. 6-89)

Figure 6-43. U-Tube Aeration Systems, a) Without Oxygen Recycle; b) with Oxygen Recycle.

Depth. The depth of the U-Tube affects initial installation costs, operational costs, and oxygen transfer efficiency. Shallower depths are less capital intensive, but result in less oxygen transfer, requiring greater throughput volumes of water and increased pumping costs to produce the daily DO tonnage required. Excessively deep U-Tubes are more costly per unit volume and induce greater hydraulic frictional losses because of the longer travel path. However, less water throughput volume is required to achieve the DO tonnage requirements because of the greater discharge DO concentrations.

Water Velocity. Water velocity within the U-Tube affects operational costs and contact time. A range of throughput velocities is feasible. At an excessively low water velocity, the bubbles would not be dragged down the U-Tube, and the high capital cost of excavation would be under-utilized. Conversely, excessively high velocities would incur large frictional losses and result in high energy consumption per unit weight of oxygen absorbed.

A similar trade-off exists between throughput velocity and cost of the U-Tube excavation. Higher velocities require less cross-sectional area for a given throughput, and vice versa.

Gas Injection Ratios. A range of gas/water injection ratios can also be utilized. If an excessively low gas/water injection ratio is supplied, the U-Tube excavation and pumping energy are under-utilized. If the gas/water injection ratio is too high, the system will "stall" and be unable to drag the high volume of gas bubbles through the system.

Two modes of operation are feasible with oxygen injection into a U-Tube: one pass (of the oxygen gas) and recycle of the off-gas. If one pass oxygen absorption is practiced, the U-Tube depth must be in excess of 60-m and the oxygen/water injection ratio must be below 3% to achieve over 80% oxygen absorption efficiency. The increase in DO will be somewhat less than 30 mg/L. Conversely, if off-gas recycle is practiced, 25% gas/water can be injected into a 30-m deep U-Tube and the DO increase will be about 50 mg/L. At the present time, off-gas recycling appears to be the best approach for U-Tube aeration of hydroelectric discharges.

Downflow Bubble Contactors

The Downflow Bubble Contact aerator, also referred to as the "Speece Cone", Figure 6-44, is a device for efficient absorption of pure oxygen that incorporates several desirable features such as prolonged bubble contact time, high gas-water interfacial area, efficient oxygen absorption, and simple concept.

Prolonged bubble contact time is achieved by introducing the water at the top of a conical vessel with an inlet velocity of about 10 ft/sec. This velocity prevents the gas bubbles from escaping out the top, and provides sufficient energy to prevent the bubble swarm within the vessel from collapsing. If the bubble swarm were to collapse, the only gas-water interface would be the cross-section of the cone at the bottom of the gas space, and transfer efficiency would suffer dramatically.

The conical slope of the vessel causes a decrease in the vertical velocity of the water to about 0.3 ft/sec. When the downward vertical velocity of the water decreases below the buoyant velocity of the bubbles (1 ft/sec), a separation occurs which prevents the bubbles from being swept out the bottom. Thus, the bubbles cannot escape at the top of the cone due to the high inlet velocity nor can they escape from the bottom because of the low exist velocity, and water contact can be maintained for any prescribed time. The contact time is usually controlled at nominally 100 seconds in order to yield maximum oxygen absorption efficiency. Contact time can be controlled by varying the relative rate of oxygen injection into the cone or by varying the relative rate of bubble harvesting. Injection of air as the oxygen source for this type of contactor is not recommended due to the high volumes of gas and the risk of dissolved nitrogen supersaturation.

Oxygen absorption efficiency will primarily depend on the hydrostatic pressure within the vessel and the oxygen/water injection ratio. It is possible to achieve 100% oxygen absorption efficiency if no bubbles are harvested from the system, but the steady state oxygen composition of the bubbles will be reduced by the dissolved nitrogen stripped from the water. The increase in DO across the system will

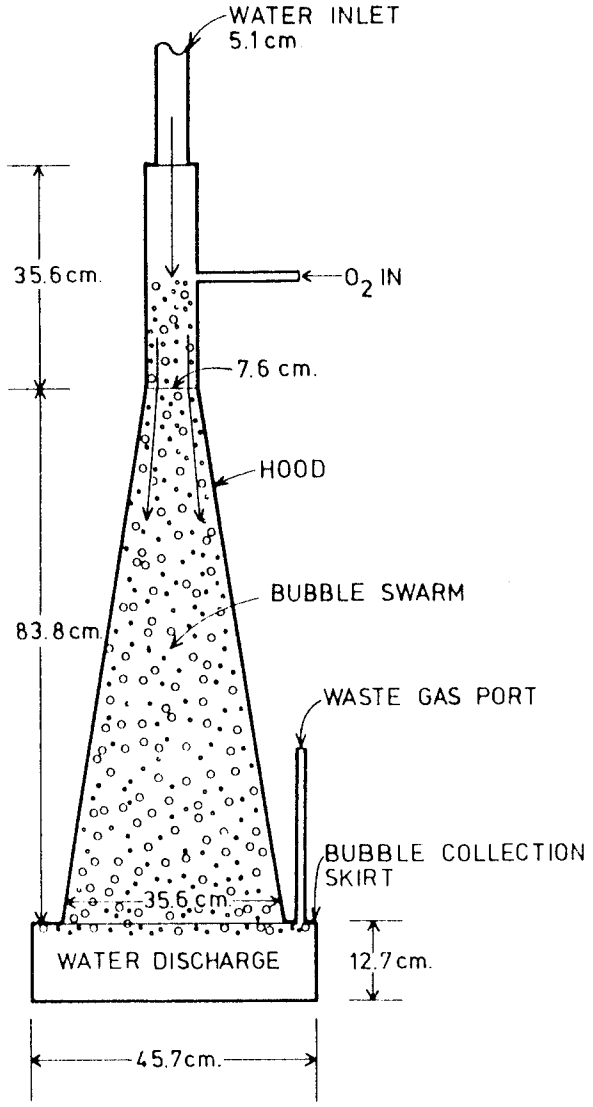


Figure 6-44. Pilot Scale Downflow Bubble Contactor

suffer accordingly. Thus, it is advantageous to harvest some bubbles from the cone system. This is accomplished by installing a bubble skirt at the bottom of the bubble swarm in the cone. As the bubble swarm is forced below this skirt, the bubbles are harvested along with the nitrogen which was stripped from solution. The deliberate harvesting of bubbles results in maintenance of higher oxygen composition as well as in higher DO increases across the system.

There is an inherent simplicity in the design and operation of the downflow bubble contractor. The system can be made of steel or fiber glass and only requires the water to move through the system against a head of approximately 15-feet. Although the system could be located in the tailrace, it should be located upstream of the turbine to maximize the hydrostatic head, which in turn maximizes the DO deficit and minimizes dissolved nitrogen stripping. With a hydrostatic head of 125-feet, the discharge DO is estimated to be in excess of 90 mg/l. Although many small downflow bubble contactors are reported in use overseas for fish culture, no hydroelectric installations are known to exist. Alabama Power Company is currently considering an installation to aerate a leakage flow of 600 CFS.

Sidestream Injection via the Aquatector

The third and final sidestream injection technique incorporates a device developed in Germany called the Aquatector. As with the Downflow Bubble Contactor, the Aquatector pressurizes a sidestream flow, supersaturates it with pure oxygen, and returns it to the main stream. The cone, however, relies upon total absorption of the oxygen into the liquid before it is returned to the mainstream, whereas the sidestream from the Aquatector is not only supersaturated with dissolved oxygen, it also contains extremely fine bubbles (< 0.002-inches in diameter) of pure oxygen. Due to their extremely small size, these bubbles have a rise time of less than 10-inches per minute, allowing them to be efficiently absorbed in the mainstream. The effective concentration of the oxygen in the discharge from the Aquatector is approximately 150 mg/L. The price paid for this high concentration is that the Aquatector requires a higher head to operate, usually 29 PSIG or more. Until recently, only small versions of Aquatectors were available, capable of treating flows of 1,000 GPM or less (approx. 2.5 CFS). However, with the current need

of hydroelectric facilities to aerate their discharges, the developer has scaled-up the design (Figure 6-45), tested a prototype, and is ready to install the first unit capable of treating large flows. The performance curve for the larger models is presented as Figure 6-46.

As with U-Tube aeration, the input design conditions for the Aquatector can be varied to meet site-specific circumstances. The device operates over a range of supply pressures (29 to 75 PSIG), water flows, and oxygen delivery rates. As with the Downflow Bubble contactor, the Aquatector could be located either in the tailrace or upstream of the turbine. The supply pressure could be supplied by the existing head pressure of the dam or by auxiliary pumps. As a rule of thumb, if 2% of the flow is sidestreamed through the Aquatector, the end result will be a 3 mg/L increase in the main flow.

Sizing Example. If a mainstream flow of 600 CFS requires additional DO of 3 mg/L, the total oxygen requirement would be 184 kg/hour (405 pounds/hour). Figure 6-46 indicates that a model 75/3000 operating at a water supply pressure of approximately 30 PSIG (slightly more than 2-bar, or 70-feet of head) and a volume of 22 CFS (2,250 m^3/hour) would be sufficient. If the head of the dam was not used to supply the pressure, the required pumping horsepower would be:

$$\frac{22 \text{ CFS} \times 70 \text{ FEET} \times 62.4 \text{ LBS/FT}^3}{550 \text{ (FT-LBS/SEC)/HP} \times 0.70 \text{ EFF}} = 250 \text{ HP}$$

Installation of the larger Aquatectors is considerably less involved than other injection devices. Requirements include a site to locate the unit (generally less than 400 square feet of floor space), the water supply pumps (if existing head pressure is not used), and a LOX facility. No large scale excavation is required. An approximate cost estimate for the above system, installed, including pumps, LOX site, intake plumbing, electrical supply, and a tailrace diffuser pipe to mix the flows, is $645,000.

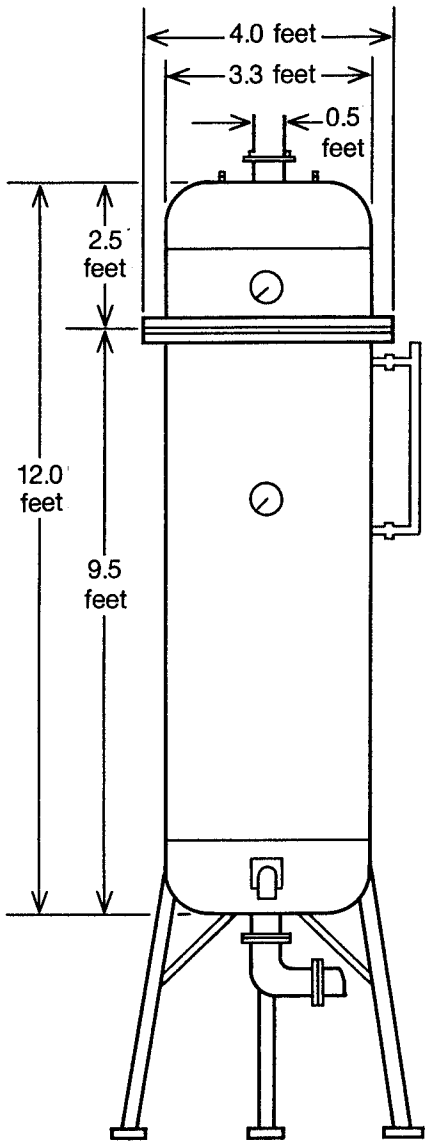


Figure 6-45. Series 75/1000 Aquatector (Courtesy of F.J. Damann Co.)

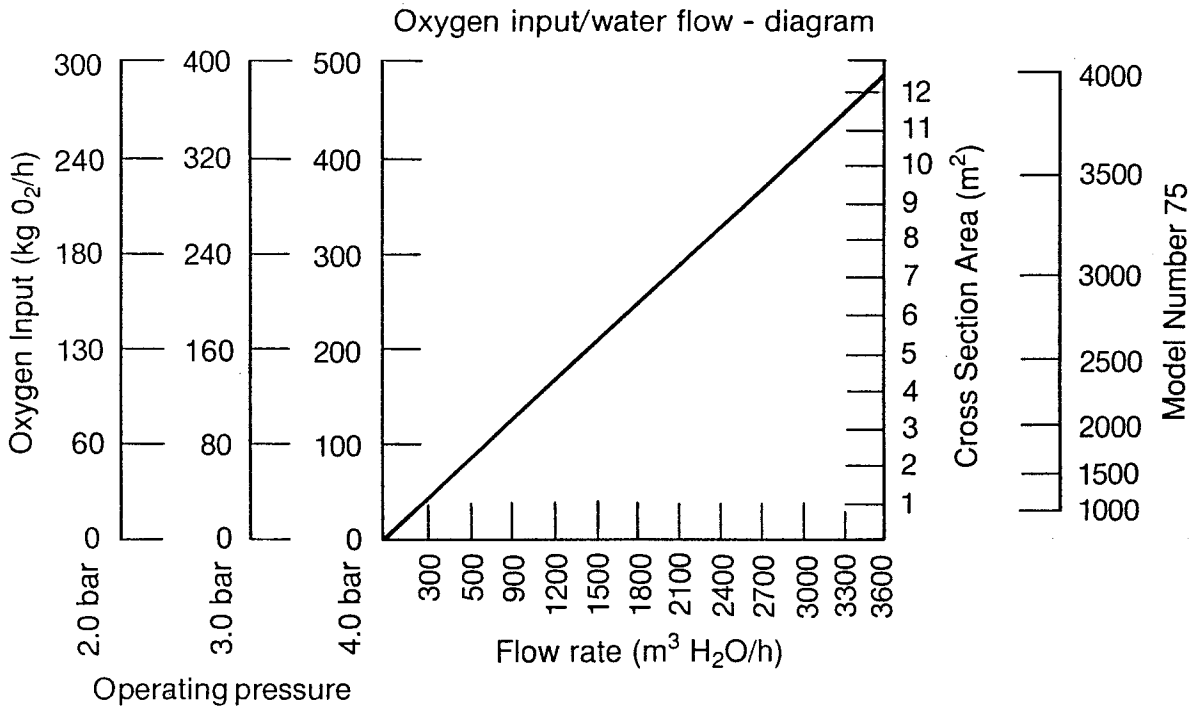


Figure 6-46. Aquatector Series 75 Performance Data. (Courtesy of F. J. Damann Co.)

Section 7

DISSOLVED OXYGEN MONITORING AND MODELING

7.1 DEFINING MONITORING OBJECTIVES

Various types of monitoring activities can be required to address the DO issue at hydropower projects. Monitoring can become a significant cost item, but if the objectives are established before initiating monitoring activities, the costs can be controlled and the value of the data can far outweigh the costs. The design of effective monitoring efforts will involve a team approach, including those responsible for the aeration system design and evaluation, water quality, aquatic life, instrumentation, reservoir operations and data analysis. Resource and regulatory agencies will also be involved.

It is important to recognize at the beginning that monitoring can be a significant activity requiring considerable staff time and costs; however, it should also be recognized that an effective program can reduce the aeration costs of meeting objectives of tailwater uses.

Generally, there are four major purposes for monitoring: (1) To establish baseline information; (2) to provide input to water quality modeling and other special assessments; (3) to evaluate aeration systems; and, (4) to comply with regulations or agreements with resource agencies.

Baseline Monitoring

Baseline monitoring is conducted to estimate the effects project development may invoke, or to determine if an existing project violates state water quality criteria. Often, one or two years of monitoring data will be collected to establish the flow, DO, temperature, and in some cases, total dissolved gas conditions that exist. Weekly grab samples from the discharge typically will capture the seasonal variations in DO, while hourly or continuous DO samples will

capture the diurnal DO variation. Continuous monitors may not be necessary for long periods of time if arrangements can be made to operate the turbine over a wide-range of operational conditions during the period of low DO and an adequate cause/effect data base can be obtained. Measuring DO for only one or two years will likely not capture the extreme seasonal conditions as discussed above, however, and longer periods of record on similar rivers or projects can be used to estimate possible extreme conditions. An enhanced baseline monitoring program could include fishery surveys. If the monitoring is being conducted prior to a project's construction, similar data should be collected after generation begins.

Calibration of Water Quality Models and Other Types of Assessments

A more intensive monitoring system is required if the owner desires to model the specific site. Modeling can be very useful in predicting the effects of changing environmental and project-related conditions that would be difficult or impossible to test in the field. Models can be used to understand how a stream will re-aerate at various flow levels, how it will respond to varying levels of oxygen-demanding substances, or to evaluate the effectiveness of aeration alternatives on downstream water quality conditions. Besides DO and flow, the data collected should include other parameters such as temperature, and possibly other determinations such as nitrogen compounds and BOD. Kim and Bohac (Ref. 7-1) have also presented an example of how a steady-state stream model can be used to examine reaeration options at a hydroelectric project.

To optimize the operation of a hydroelectric project in relation to water quality, an unsteady-state water quality model probably will be necessary. Unsteady-state models are also useful for simulating DO conditions for exposure analysis for fish. Such models require considerably more data than steady-state models, particularly in regard to stream geometries and continuous DO, temperature and flow data. Hauser (Ref. 7-2) presented an example of the use of an unsteady-state model for predicting the water quality effects of alternative release schedules from a hydroelectric project.

In even more intensive monitoring systems, the objective may be to model the oxygen dynamics of a reservoir to determine how and when

the oxygen is depleted. For example, it might be important to determine whether incoming flows or reservoir weed growth is responsible for the depressed DO concentration in hydroelectric releases. Reservoir water quality models are far more data intensive than stream models and generally require weekly to monthly sampling for 6-9 months for calibration, and consideration of a second year's data for validation. Typical data collected for a two-dimensional reservoir model include inflow-outflow sediment oxygen demand, inflow and reservoir nutrients, and organic concentrations, algae concentrations, turbidity and temperature profiles with depth. Hauser, et al (Ref. 7-3), present an example of using a two-dimensional reservoir model for examining the DO in hydropower releases.

Special monitoring can also be conducted in conjunction with special assessments to achieve some of the same objectives without going to the extent of employing models. For example, the rate of DO recovery in the tailwater can be determined during steady-state turbine discharges when the DO is at various concentrations. Worse case conditions occur when DO is the lowest in the releases and when the turbines are operated at highest probable flow. Periodic DO and temperature profiles in the reservoir can provide much information on the nature of the DO concern, simply by comparing the characteristics of the DO patterns with those of other reservoirs described in section 3 and in the literature. Such limited DO assessments coupled with other information on point sources and the nature of nonpoint sources on the setting of the project can provide much practical input to a limnologist or engineer experienced in such assessments.

If DO concentrations in the releases are near zero, other water quality constituents of concern will include dissolved iron and manganese and hydrogen sulfide. Special assessments will be needed to determine the extent of the concern if these constituents are found to be present.

Aeration System Design

Monitoring systems to establish design conditions for aeration systems will be similar to those designed to establish site-specific baseline conditions for the project. The design of the aeration

system, however, will require more intensive monitoring in the near vicinity of the dam.

Monitoring for aeration system design is an excellent example of why a baseline-monitoring plan would be expanded. Some owners will spend 6-months to a year monitoring the minimum number of parameters to establish baseline conditions, only to have to repeat the study in its expanded version to gather enough information to permit the sizing and evaluation of various aeration systems. The expanded monitoring incorporates additional sampling sites and perhaps a higher sampling frequency. If the equipment from the baseline study can be expanded to accommodate the additional hardware, all that is lost is 6-months to a year's time, and the labor to sample and maintain instrumentation. If the original equipment is not expandable, considerably more hardware will be purchased.

The purpose of the aeration tests is to determine the efficiency of an aeration system generally under varying turbine discharge conditions. The tests are made to determine the performance of a new aeration system in respect to meeting specified requirements and/or to enable scaling of the tested system to provide the amount of oxygen ultimately required.

In addition to establishing the design parameters for aeration system alternatives, the same monitoring system will be used to verify the performance of the final aeration measures, and possibly, to control its operation. It can also be used to assure compliance to the state water quality standard or other water quality objectives.

Compliance Assurance

The final category of objectives for monitoring is that of compliance assurance. In nearly all cases, some form of earlier monitoring is likely to have occurred at the site, and the compliance monitoring system will be some version of the earlier effort. Depending on the particular site and the dynamics of the dissolved oxygen problem, compliance monitoring can be as simple as an infrequent grab sample, or as elaborate as a continuous system that also serves to control aeration devices. If the DO concentration is consistent from day to day such as the DO characteristic from a deep, well stratified

reservoir with the turbine intakes well below the thermocline, grab samples on a weekly or biweekly basis would suffice.

If, however, the system is used to simultaneously monitor for compliance and to control the aeration system, the monitoring must be designed in conjunction with the aeration control system to make sure that the two are compatible. If the response to a change in the aeration system considerably lags the control signal, the monitoring system must be located in such a place that warning can be given to the operator or the appropriate signal supplied to the automatic control system well in advance of the need to make a change in the aeration system's operation. The most extreme example of necessary lead time would be for a continuous oxygen injection system in which the oxygen is added to the water hours or even days in advance of the water's release through the turbines.

If the monitoring automatically controls the aeration system, a signal indicating a low DO value might trigger the operation of the next increment of aeration capability. This might be the opening of a control valve on an air compressor to provide more air to a aeration system, the addition of another compressor to the system, the increase in oxygen flow to an oxygen injection system, or the resetting or an aerating sluice valve to a more open position.

Thus, compliance monitoring can become as varied and as involved as any other type.

7.2 FERC MONITORING PLAN REQUIREMENTS

This discussion is meant to address the DO monitoring requirements typically found in recent FERC licenses. It should be noted, however, that the Commission's position regarding dissolved oxygen levels may be changing, and monitoring requirements could be radically affected. As discussed below, license requirements have generally focused on both investigating and resolving the DO issue. Because both the owners and agencies have become more aware of the dissolved oxygen issue, future licenses may not be issued until DO has been investigated and the problems resolved. If this is the case, the

owner will have to implement a monitoring plan at a much earlier date. The plan will have to be suitable to both the owner's purposes and those of the consulting agencies. The monitoring results will have to be analyzed and the issues resolved before a license is obtained. The issued license would only address the applicable standard and the basic post-operational monitoring requirements to assure compliance.

Typical DO Monitoring Plan

Typical of FERC monitoring requirements is the following article from the Order Issuing License for the Nockamixon Hydro Project (No. 8662), dated April 6, 1987:

> Article 402. The licensee, in cooperation with the Pennsylvania Department of Environmental Resources, Pennsylvania Fish Commission, and the U. S. Fish and Wildlife Service, shall develop a water quality plan to monitor the pre- and post-construction dissolved oxygen and temperature levels of Tohickon Creek and the Nockamixon Reservoir. The plan should include measures necessary to effect alteration of project operation or structures, including installation of aeration devices, to ensure protection of the fish resources of the project reservoir and Tohickon Creek and maintenance of state water quality standards. The plan shall be filed with the Commission for approval within six months from the date of issuance of this license. Comments from the agencies shall be included in the filing.

Articles addressing DO monitoring plans normally contain:

1. a list of agencies that must be consulted;
2. a requirement that agency comments must be submitted with the plan;
3. a requirement to include measures for alteration of project operation or structures should DO levels fall below state water quality standards; and,
4. the period of six months to prepare and submit the plan.

Depending on the circumstances, pre- and post-construction monitoring plans may not both be required.

When submitted, the plan is generally in the form of a letter, with agency comments attached. The letter generally quotes the original article and includes a brief description of the project, followed by the plan itself. Due to submission date requirements, plans must

often be submitted prior to receiving all agency comments. As formal comments are received, subsequent addenda can be made to the original filing.

The following excerpt is from the plan submitted to FERC for the Nockamixon Hydro Project:

> Water Quality Monitoring Plan:
>
> The project will be operated as a run-of-river facility. The project will be able to use flows from about 7 to 260 cfs for power generation. During the months the lake is stratified, water will only be taken from the upper two gates in the intake tower to reduce the amount of oxygen depleted water released downstream to Tohickon Creek. If DO falls below the required level, the number two gate will be closed, only allowing water to pass through the uppermost gate of the intake tower.
>
> Studies will be conducted with alternative operating plans when the plant is completed. This plan will include operating the plan during periods when the lake is stratified, with all four intake gates open with the anticipation that surface water will be drawn to the lower gates. This may help mix the lake near the intake tower. If DO levels fall below State standards, this potential operating plan will be rejected.
>
> Chapter 93 of the Water Quality Standards for Pennsylvania for a cold water fishery will be met. These standards are:
>
> Temperature: No rise when ambient temperature is 58 degrees F. or above; not more than 5 degrees 5. rise above ambient temperature until stream temperature reaches 58 degrees F.; not to be changed by more than 2 degrees F. during any one-hour period.
>
> Dissolved Oxygen: Minimum daily average 6.0 mg/L; no value less than 5.0 mg/L. For lakes, ponds and impoundments only, no value less than 5.0 mg/L at any point.
>
> In order to ensure that acceptable levels of DO and temperature are being released downstream, NHA will continuously monitor releases downstream. Also, NHA will sample water quality prior to project operation. Pre-project sampling will occur during construction of the project. Construction is expected to begin in the Spring of 1989 and last through the Fall 1989. This will cover the period of the year when the lake is stratified.
>
> Water samples will be taken with a DO polarographic meter. Pre-operational sampling will occur one day per week. A morning and evening sampling, the same day, will be performed. The sampling station will be located in the project tailrace, upstream from the confluence with the still-

ing basin flow. During project construction, provisions will be made to install the continuous DO monitor in the tailrace for use during operation of the project.

Once the project is operational, DO and temperature will be continuously monitored in the tailrace. The monitor being considered at this time is the ENDCO Water Quality Monitor, Model 1112. This monitor can be programmed to take readings at varying intervals. It is anticipated that a reading every 15 minutes will be adequate to cover changes in DO and temperature. Also, during project operation, lake profiles of DO and temperature will be periodically taken at the intake tower.

NHA will continuously monitor the water quality of the project and alter operations when DO falls below State standards. Operational alterations may consist of either throttling back the turbine output at approximately 10% intervals and increasing flow at the dam or through the existing Howell-Bunger valve, or closing the second level gate int he intake tower, utilizing only the upper gate.

There have been no provisions made for installing additional mechanical aeration devices as it is possible to operate above State standards, year around, given the flexibility of selective withdrawal at the intake tower and the possible use of the H-B valve. In no instance will the project operate below State standards. If in the unlikely event, releases fall below State standards, the project will shut down. Further, if this unlikely problem continues on an annual basis, provisions will be made to incorporate some type of mechanical aeration device. Construction and operation of this device will be coordinated with the FWS, PFC and the DER.

Note that the plan includes the operational procedures to provide discharges that meet state water quality standards. To assure compliance, the licensee plans to continuously monitor DO levels downstream of the project. To satisfy pre-construction monitoring, weekly sampling will be performed. It is critical that monitoring plans state what method will be used to determine DO levels, and where the measurements will be taken. Finally, the licensee has allowed for unforeseen problems and has provided a commitment to solve them.

For this particular project, FERC issued an Order Approving and Modifying In Part A Water Quality Monitoring Plan on May 11, 1988. Frequently the orders issued by FERC contain slight modifications. The order reads as follows:

UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

Nockamixon Hydro Associates Project No. 8662-003

ORDER APPROVING AND MODIFYING IN PART A
WATER QUALITY MONITORING PLAN
(Issued May 11, 1988)

Nockamixon Hydro Associates (licensee) filed on February 8, 1988, and supplemented on March 21, 1988, a plan to monitor dissolved oxygen (DO) and temperature in Tohickon Creek below the project and in Lake Nockamixon, as required by article 402 of the license for the Nockamixon Hydro Project.

The licensee proposes to monitor DO and temperature of project outflows on a weekly basis prior to project construction, and to monitor outflows continuously after the start of project operation. The licensee also proposes to periodically monitor DO and temperature in the lake.

The Pennsylvania Fish Commission (PFC) and the U.S. Fish and Wildlife Service (FWS) concurred with the proposed monitoring plan by letters dated March 14, and January 14, 1988, respectively. The Pennsylvania Department of Environmental Resources (DER), by letter dated February 12, 1988, stated that the plan should include the monitoring of pH, sulfide, ammonia nitrogen, total and dissolved phosphorous, iron, manganese, and biological oxygen demand. The DER also states that project operation may alter lake stratification, thereby impacting aquatic life, and states that the licensee's proposed sampling of lake conditions from the project intake tower is not acceptable.

Article 402 requires the licensee to submit a plan to monitor dissolved oxygen and temperature. DO and temperature are considered to be the most important water quality parameters that could be influenced by the operation of the project. The other water quality parameters suggested by the DER, therefore, are not included in the monitoring plan.

The licensee's proposed monitoring would provide sufficient information to ensure that the state water quality standards for these parameters are not violated. However, the plan did not include a schedule for conducting the lake sampling, or provisions for reporting the collected data to the resource agencies and to the Commission.

In order to adequately monitor the impacts of the project on dissolved oxygen and temperature in Nockamixon Lake, the licensee should conduct DO and temperature profiles of the lake on a biweekly basis, from May 1st through October 1st. Samples should be taken at a minimum of 2 located in the lake. The location of the sample stations should be determined after consultation with the PFC, FWS, and DER.

In order to ensure that violations of state standards are immediately remedied, the licensee should notify the PFC, FWS, DER, and the Commission within five (5) days of the occurrence of any violation and identify the measures that were implemented to correct the violation. In order to allow the resource agencies the opportunity to review the collected monitoring data, the licensee should provide the resource agencies with collected data within 30 days from the date of any request for the data.

The implementation of the licensees' proposed water quality monitoring plan, with modifications discussed above, would ensure the maintenance of state water quality standards during project operation.

The Director Orders:

(A) The water quality monitoring plan filed on February 8, 1988, and supplemented on March 21, 1988, and as modified by paragraphs B through D, is approved.

(B) The licensee should conduct temperature and dissolved oxygen profiles of Lake Nockamixon on a biweekly basis from May 1 through October 1. Samples should be taken at a minimum of 2 locations in the lake. The location of the sample stations should be determined after consultation with the Pennsylvania Fish Commission (PFC), the U.S.Fish and Wildlife Service (FWS), and the Pennsylvania Department of Environmental Resources (DER).

(C) If a violation of state water quality standards occurs, the licensee shall notify the PFC, FWS, DER and the Commission's Division of Project Compliance and Administration, within 5 days of the occurrence of the violation, and identify the measures that were implemented to correct the violation. Upon being notified of violations, the Commission reserves the right to require additional modifications to the monitoring plan, or to require changes to project operation or structures to ensure maintenance of dissolved oxygen and temperature at state standard levels.

(D) The licensee shall provide the PFC, FWS, and DER with collected data within 30 days from the date of any request for the data.

(E) This order is issued under authority delegated to the Director and is final unless appealed to the Commission under Rule 1902 within 30 days from the date of this Order.

FERC noted that the plan did not include a schedule for DO monitoring, or provisions for reporting the data to the agencies. The Commission added the schedule and the provisions. Further, two locations were specified for lake measurements, the exact location of which were to be decided in consultation with the other agencies involved. Somewhat unusual is that the licensee is only to provide data when requested. More typically, annual reports are required to all involved agencies. The data-upon-request approach will probably cause less confusion over time, but may also allow poor water quality situations to go unnoticed. FERC does, however, require the licensee to notify the agencies should sub-standard conditions occur, and the actions to be taken to correct the matter.

Finally, as is typical in all orders, the Commission has reserved the right to modify the plan or to require additional modifications should the existing plan not provide for state water quality standards to be met.

In summary, typical DO monitoring plans submitted to FERC should contain:

1. sampling method (DO meter, Winkler Titration, etc...);
2. sampling location (should be decided upon through agency consultation; upstream reservoirs should minimally involve two sites);
3. schedule of sampling (may vary throughout year, with most samples taken during low flow/high water temperature/low DO periods);
4. contain plans to alter operation/aerate discharges to meet state water quality standards;
5. comments from the specified agencies that were consulted on numbers 1 through 4.

Additional Examples of DO Monitoring Plans

Hydropower Project, Lewiston Falls, Maine. An extensive pre-operational water quality program was carried out at this project according to a plan filed with the FERC in August of 1977 to address a condition in the FERC license. The study plan incorporated comments by resource agencies interested in the project. The study objectives

were to expand the existing water quality data base and establish a pre-operational baseline with which to compare post-operational conditions. The second object was to collect data to calibrate and verify a mathematical DO model to identify potential reaeration sources that would help mitigate any reduction in DO caused by the project. DO and temperature were monitored with grab samples at approximately 20 locations. A State of Maine Department of Environmental Protection protocol was used for DO and temperature sampling. Low flow periods were selected for sampling on the basis of when the product of temperature and flow duration, expressed as a percent, exceeded 1500. During each sampling period, eight samples were taken over a 72-hour period. In addition, other parameters such as temperature, nitrate, and biochemical oxygen demand were also measured. The data were to be collected during a low flow/high temperature event. In addition, three continuous DO monitoring stations were established to measure DO from June 15 through September 15.

At the beginning of project operation, DO was measured at a bridge pier a few hundred yards below the dam. A DO probe, analyzer, and recorder were attached to the pier. Periodically, the installation is serviced by a boat, the instrument recalibrated, and the data (in this case, a paper tape) retrieved. An additional monitoring station is located three miles downstream. Samples are obtained at this station by pumping water from a sampling port located in the middle of the river to a monitoring facility located on the shore where the DO and temperature are continuously monitored and recorded. Data are telemetered back to the powerhouse where the DO readings can be used to control the aeration systems. Flow is recorded at the powerhouse. The licensee contracted with the United States Geological Survey to construct and maintain the monitoring stations. Monitoring at the downstream stations is on a seasonal basis from June through September.

Beginning in 1988 and through 1990, the DO criteria at this project are that the DO must not fall below 5 mg/L on an instantaneous basis and not below 6.5 mg/L on a 30-day average basis.

Toledo Bend Dam Hydroelectric Project, Texas. In 1986, the project license was amended to allow for the addition of a 750-kW hydroelec-

tric turbine to generate power from water being released to provide a minimum flow in the river below the dam. The licensee was able to supply FERC with DO and temperature data provided by the Texas Authority's Environmental Services Division who routinely monitors water quality in the reservoir and the river.

In addition to these data, FERC requested additional information on temperature, pH, and DO in the immediate tailrace area below the discharge of the proposed new unit. As a result, five additional downstream monitoring stations were established in the tailrace area. Sampling was conducted biweekly at these stations from May to November in 1986. The data suggested that the project additionally would be able to provide a minimum of 5 mg/L in the discharge which is the stream standard below the project. The license amendment stipulated that:

> The licensee, in cooperation with the Louisiana Department of Environmental Quality, Louisiana Department of Wildlife and Fisheries, Texas Department of Water Resources, and Texas Parks and Wildlife Department, shall develop a dissolved oxygen (DO) monitoring plan. The plan shall include provisions for the rapid alteration of project operation to ensure maintenance of State DO standards immediately downstream from the low-flow sluiceway. The plan shall be filed with the Commission for approval within 6 months from the date of issuance of the license. Comments from the aforementioned agencies on the plan shall be included in the filing (36 FERC, Par. 62, 166, Article 402).

The monitoring plan submitted to the FERC for operation of the project stated that the downstream stations established for the pH, temperature, and DO study would continue to be monitored on a biweekly basis. If a DO concentration below the stream standards were detected, the following course of action would be taken.

Step	Action
1	Low DO detected
2	Immediately initiate additional sampling
3	Verify the measurement in question
4	Immediately notify operations personnel upon verification

5	Operations personnel release oxygenated water via one of eleven tainter gates
6	Field sampling team continue monitoring
7	Monitoring would be increased to diel frequency until DO levels reach stream standards
8	Special sampling would be undertaken to define cause of low DO concentration
9	Special data collected would be used for corrective measures to prevent recurrence.

Kaw Hydroelectric Project, Oklahoma. This project was required to conduct a field monitoring program for two years (1987-1988) prior to project startup. The objective was to determine baseline conditions which would help in the development of the project operating schedule. Monitoring was conducted both in the reservoir and in the tailwater. Reservoir monitoring was conducted to determine the frequency and extent of stratification in front of the turbine intakes. Monitoring was conducted weekly from June through October. Reservoir profiles were obtained for DO, temperature, pH, and conductivity. Tailwater monitoring consisted of measure DO, temperature, conductivity, and pH at three depths at three stations across the tailrace about 500 feet below the dam. Daily inflow and discharge volumes and the mode of discharge were also recorded (Ref. 7-4).

The monitoring program was developed in consultation with the Oklahoma Water Resources Board, the Oklahoma Department of Wildlife Conservation, and the United States Army Corps of Engineers.

Kingsley Dam Hydroelectric Project, Nebraska. A hydropower addition was made to this irrigation project which required a change in the license. The project was allowed to operate on the basis of an annual license under the conditions of the old license while the new license was being obtained. Because the dam was originally built for irrigation, the releases from the dam prior to the hydropower addition were made by sluicing and DO problems were never observed. However, depressed DO concentrations were observed in the first year of hydropower operation. As a result, the Nebraska Department of Environmental Control, the Central Nebraska Public Power and Irriga-

tion District, and the Nebraska Game and Parks Commission jointly conducted extensive water quality monitoring activities to determine the DO conditions in the upstream reservoir, the tailrace, and the downstream reservoir. DO, temperature, hydrogen sulfide, total gases, and nitrogen gas were measured at nine locations weekly over a one-year period. At four of the locations, continuous recording monitors for DO and temperature were installed. In addition, creel census information and benthic invertebrate data along six transects were collected. Creel data included raw count, fishing pressure, and harvest estimates while invertebrate data included total number of taxa, and diversity.

The objectives of the study were to: (1) Define temporal and spatial trends in the chemical and physical environment of the downstream tailwater affected by the project. (2) Define existing biological populations inhabiting the tailwater and monitor a stocked rainbow trout population. (3) Evaluate the effects of Kingsley Hydro operations on the chemical, physical, and biological environment of the tailwater. (4) Provide sufficient data to develop site-specific water quality criteria necessary to support appropriate designated beneficial uses, including seasonal uses, in the tailwater (Ref. 7-5).

On the basis of the study, DO requirements were imposed which require the facility to add oxygen to the turbine discharge or spill water through an aerating sleeve valve in order to meet the requirements. The owner has chosen to use the sleeve valve.

Operational monitoring is conducted approximately 500 feet below the dam where DO is measured every 10 minutes. The DO monitoring equipment is installed in a buoy which floats in the middle of the tailrace. The monitoring signal is transmitted back to the powerhouse where a computer processes and stores the data and provides a control signal for operation of the aeration valve.

The DO requirements for the project are an instantaneous minimum of 3 mg/L (no single 10-minute value below 3), 100 percent of the daily averages (average of 10-minute samples) are to exceed 4 mg/L and 80 percent of the daily averages are to exceed 4.1 mg/L. The 7-day

average for the daily averages is to exceed 4.3 mg/L (Ref. 7-6). These criteria are less than State standards. Therefore, in this case, the additional studies required to obtain site-specific criteria were probably economically justifiable in terms of power sales.

7.3 MONITORING SITE SELECTION FACTORS

The objective of selecting a monitoring site is to insure that samples are representative of the water in question. Hydropower discharges can be massive and the distances and flow cross sections characterizing a site can also be great. The greater the discharge and physical dimensions, the more complex monitoring site selection becomes. The mixing zone is defined as that zone below which the water is thoroughly and uniformly blended together with no variation of parameters in the flow cross section. This requires time and distance to accomplish. Aerial views of large converging rivers, one muddy and the other clear, confirm that it may be miles downstream from the convergence before the two rivers are uniformly blended. Complex situations may require dye injection studies to define the mixing zone. Improper selection of a monitoring site may either result in artificial compliance or violation of discharge regulations. Listed below are a number of areas that should be carefully considered when selecting monitoring sites for both the reservoir and the tailrace:

Discharge Rate
Physical Configuration
Reservoir Characteristics
Turbines in Operation
Time: Daily and Seasonal
Spilling vs Generating
Tailwater Depth
Leakage

Discharge Rate

Greater discharges tend to possess greater momentum and velocity. The greater momentum may hinder mixing of two parallel discharges or enhance mixing of two perpendicular discharges. The greater velocity tends to extend the length of the mixing zone. Conversely, a low flow discharge creates less turbulence and may have as great a mixing

zone as a large flow. A generalization cannot be made of the mixing zone of large vs small discharges without site-specific details.

Physical Configuration

The width of the downstream channel will have a strong influence on the length of the mixing zone. Wide channels magnify the length and narrow channels reduce it. The roughness of the downstream channel is also a factor in that large boulders increase mixing and shorten the length required to achieve uniform conditions. The power plant might be located at one end of the dam or be spatially removed from proximity to the dam with the hydro-discharge into a side channel that enters the main channel quite some distance downstream.

Reservoir Characteristics

Velocities in the reservoir are much affected by density gradients during stratified conditions. For instance, a colder upstream discharge as from an upstream dam discharging hypolimnion water may flow as a "sandwich" layer through a downstream impoundment. The elevation of the downstream penstock intake is an overriding factor. For example, a low-level intake may allow discharge of the colder bottom water and storage of a warm water inflow. A submerged weir located upstream of the penstock intake would affect the strata of the reservoir drawn into the turbines. Furthermore, the rate of turbine discharge will determine the effective withdrawal zone in a stratified reservoir. It is not a trivial task to predict the discharge characteristics from a stratified reservoir, because many site-specific, time dependent characteristics are involved.

Turbines In Operation

The spatial separation of the turbines has a strong influence on the mixing zone. Usually an attempt is made to operate all turbines for equal times so that the same turbine is not always used. For instance, if a minimum discharge is mandated during nights or weekends, the mixing zone will vary depending on which turbine is in use.

If a small "house" turbine is used to supply power to the dam, it may be the only unit operating at times. The "house" turbine may be located on the opposite side of the dam, and it may even draw water from a different strata within the reservoir. Operation of the

"house" turbine will result in a totally different mixing zone downstream.

Time: Daily And Seasonally

During the colder season of the year during which the reservoir is not stratified, there is less variation in discharge water quality characteristics and, therefore, relatively fewer problems in proper siting of a monitoring station. However, the warmer season with concomitant stratification will present the most difficult scenario for proper siting. Daily variations during the stratified season can compound problems in defining the location of the downstream mixing zone.

Spilling vs Generation

The most significant difference between spilling and generation discharges is the energy dissipation involved. Generation removes more than 90% of the energy, transferring it to the turbine, while spilling dissipates all of the energy in the stilling basin. Therefore, the mixing zone would be considerably shortened for spilling compared to generation discharges. Obviously, the withdrawal strata would also be different in each case.

Tailwater Depth

Some hydropower facilities discharge into free-flowing channels with the depth controlled by the discharge rate and the backwater curve. Other facilities may discharge into a downstream impoundment or re-regulation reservoir. In the former, the channel may be dry when no discharge occurs and then fill to a depth of several feet during the maximum discharge. When daily discharge is terminated, the depth gradually returns to zero. In the case where discharge is into a re-regulating reservoir, there is considerable depth and the horizontal flow velocity will be reduced accordingly. Depth and velocity will affect the mixing zone.

Leakage

Some dams have leakage that can amount to hundreds of cubic feet per second. Two important characteristics of this leakage can affect the proper selection of a monitoring site. First, the leakage may enter the downstream channel hundreds of feet below the dam. Second, the

inherent characteristic of the leakage is that it originates from the bottom water in the reservoir and it travels through pores or fissures in the underlying strata, both of which could result in oxygen depletion. Therefore, a monitoring site located between the dam and the leakage inflow may indicate satisfactory DO during periods of no discharge, when, in fact, the downstream leakage flow is severely DO deficient.

Summary

Proper selection of a monitoring site must take into account all of these considerations. The validity of water quality data can be nullified if the monitoring site examines water samples unrepresentative of the entire downstream cross section. A considerable amount of time and resources can be justified to ensure that under all possible operating conditions, a proper monitoring site is located so that representative water samples are withdrawn for analysis. Selection of a site should be based upon the homogeneity of the readings taken over a cross-section of the flow, with the facility at various operating modes, at different periods of the year. The validity of monitoring sites should be periodically checked. It is recommended that samples be taken from the river cross section at the site and compared with the samples from the monitoring site proper.

It is also recommended to reconsider the location of sites both during the testing of aeration systems, and after the systems have been put into permanent operation. Reservoir conditions can change with the application of reservoir aeration techniques, and tailrace characteristics will be affected by techniques that incorporate bypass valves and gas injection equipment.

In all cases, however, whether testing for compliance or testing aeration system performance, the involved agencies must approve the location of the monitoring sites.

7.4 FREQUENCY OF MAKING WATER QUALITY MEASUREMENTS

Parameters And Objectives

The frequency of making water quality measurements is dependent upon the parameter to be measured. Because instrumentation exists for

continuously measuring parameters such as DO, temperature, pH, and conductivity, these parameters can be physically measured far more frequently than other parameters where the measurements must, for the most part, be more discrete. These latter types of parameters include biochemical oxygen demand (BOD), iron and manganese, and nutrients such as nitrogen and phosphorus compounds which are generally sent to analytical laboratories for analysis.

The objective (see section 7.1) for sampling the water quality also determines the frequency at which parameters are monitored. For example, in the early stages of a licensing study, the objective might simply be to obtain background water quality data. In this case, only a few surveys in which grab samples are obtained may be sufficient to determine whether a low DO condition exists. However, if a monitoring program is to be developed for establishing baseline water quality conditions in order that pre-generation and post-generation DO effects can be compared, a comprehensive monitoring program would be required.

When considering the frequency of monitoring for DO effects, an important aspect to always keep in mind is its variability. There are two types of variability that should be considered. The first is the seasonal change in DO. DO conditions are generally highest in the coldest months because the lower temperatures provide for the greatest potential saturation, the decreased temperatures slow oxygen-consuming biochemical reactions, and the potential for thermal stratification is generally at its lowest for the year. In warmer months, the potential saturation is lowest, oxygen-consuming reactions are at their highest rates, and the effects of any thermal stratification will likely become apparent. Figure 7-1 shows the yearly trend in DO and temperature on one of the Tennessee River dams. The data are from weekly grab samples and are suitable for depicting the seasonal trends in DO.

With data collected over a one- to two-year period, it is likely the extreme seasonal conditions will not be contained in the database. Figure 7-2 shows the range of the weekly data collected over a period of approximately 15-years at the same project as shown in Figure 7-1.

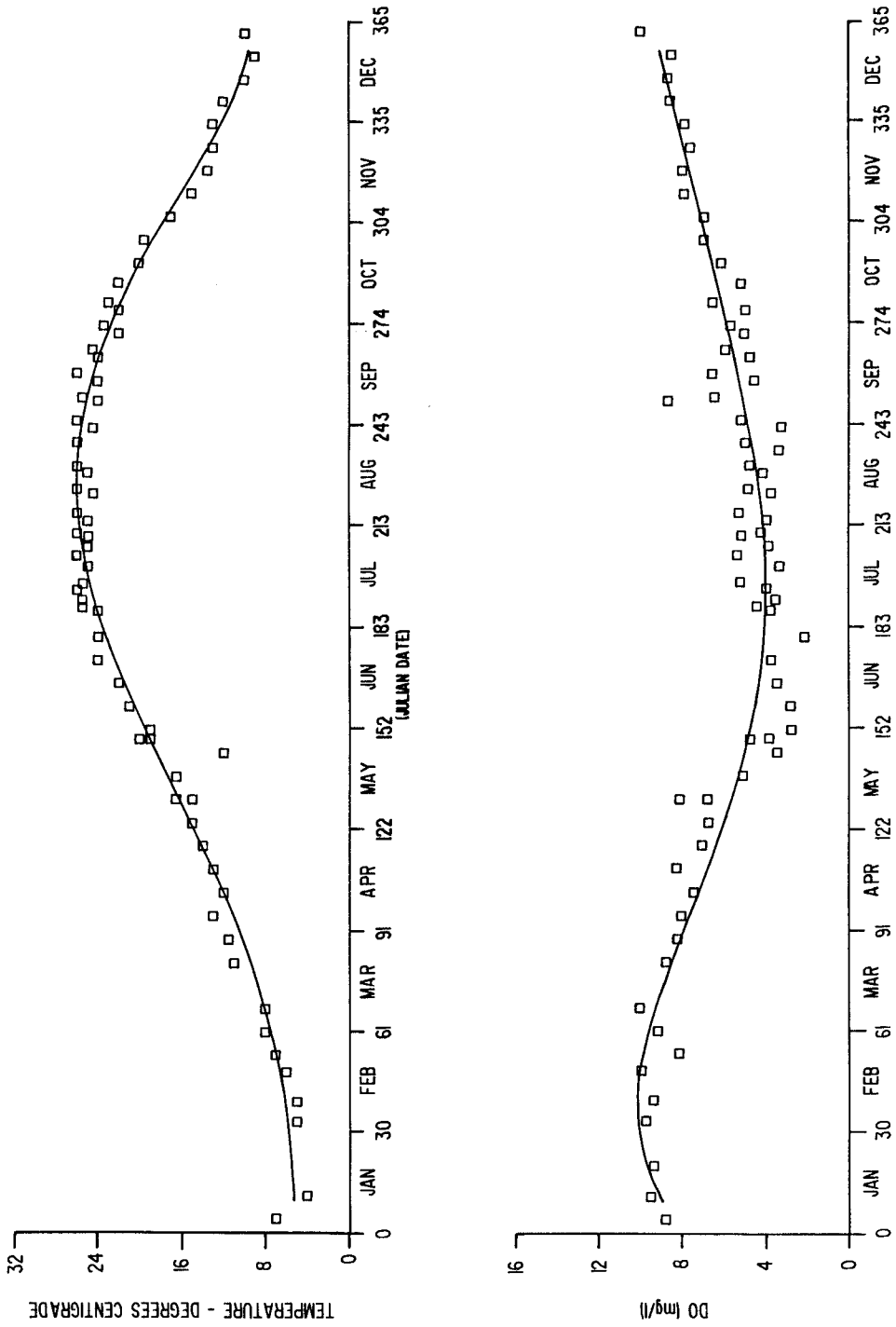


Figure 7-1. Temperature and Dissolved Oxygen at Watts Bar Dam, 1982

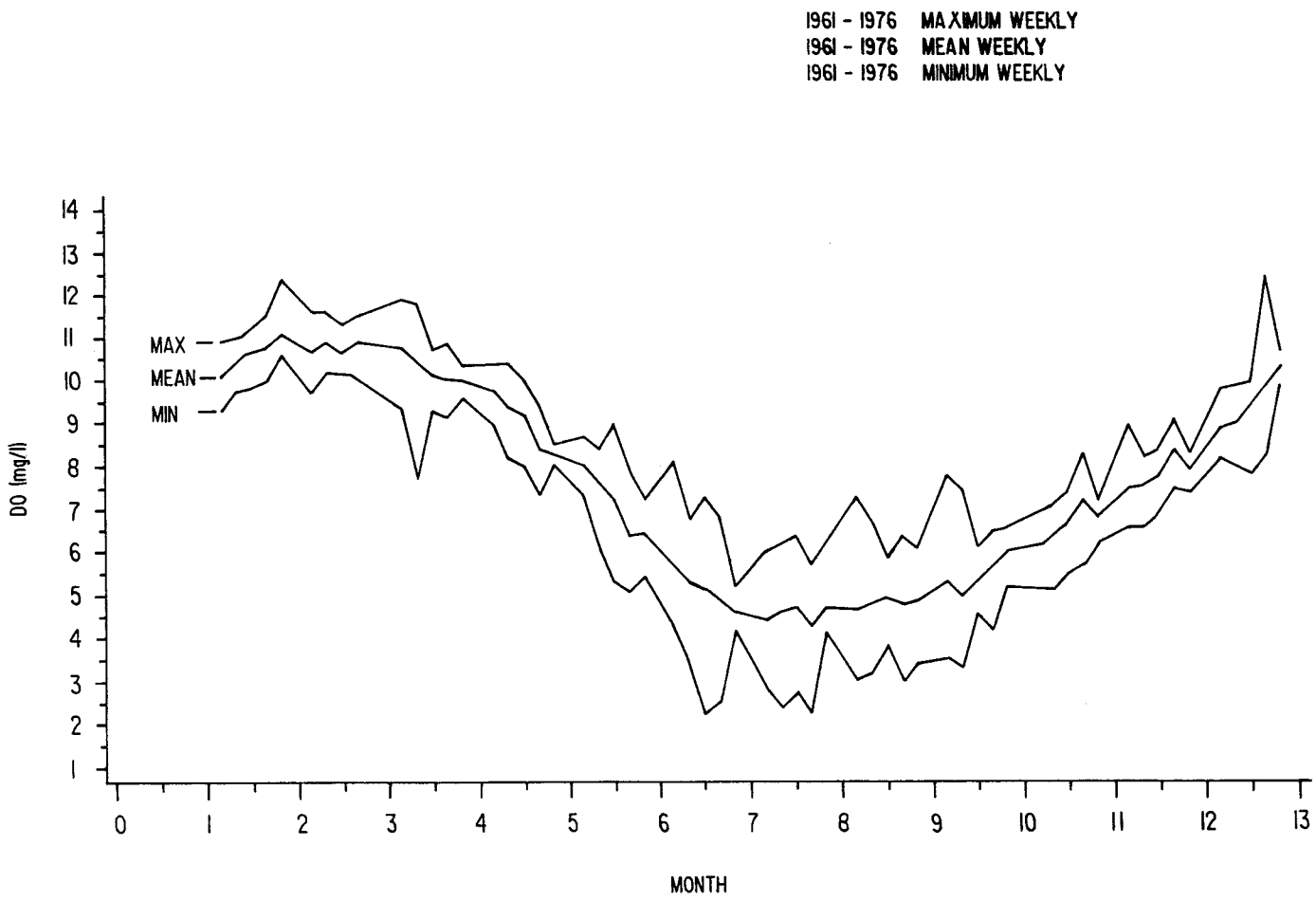


Figure 7-2. Historical Dissolved Oxygen at Watts Bar Dam

Because DO has likely not been an issue over an existing project's lifetime, the DO record for many projects seeking a new license might be relatively short. One should, therefore, realize that the long-term extremes of seasonal variations in water quality might be significantly different from the extremes obtained in a one- or two-year period of record. (Reservoir modeling techniques can predict long-term extremes using a database minimally covering a two-year period.)

The second type of variation deals with how operation of a project might change water quality over the course of a day's time. Significant water quality fluctuations might occur at such reservoirs where the discharge varies widely over a day's time, especially in combination with a thermocline that is affected by the withdrawal zone of the turbines. Figure 7-3 shows the variation in DO from a hydropower plant since the time the turbines came on-line that day. Conversely, dams with deep reservoirs with intakes well below the thermocline are likely to exhibit very stable DO concentrations with time.

A third type of variation in DO arises from photosynthesis and respiration of aquatic plants such as algae. These factors are extremely important to the variation in DO in a stream and cause the DO to vary with time of day. These phenomena can be very important in monitoring the DO in streams below dams because they can cause the DO to be higher or lower than that observed in the releases. Figure 7-4 shows how DO varies in a stream with time of day in two ways. The first is the variation one would observe by following the same slug of water downstream and measuring the DO as the water travels. The second is to measure DO at the same point in the stream as a function of time.

Another important factor which can vary the water quality of a river is the rate of flow. Flow can change the DO in several ways. The first way is that the reaeration rate is a function of turbulence. Changing the flow will change turbulence and hence the reaeration characteristics of the river. A change in flow will also change the time the water takes to travel from the dam to the observation point. This will change the time available for reaeration. A third way the

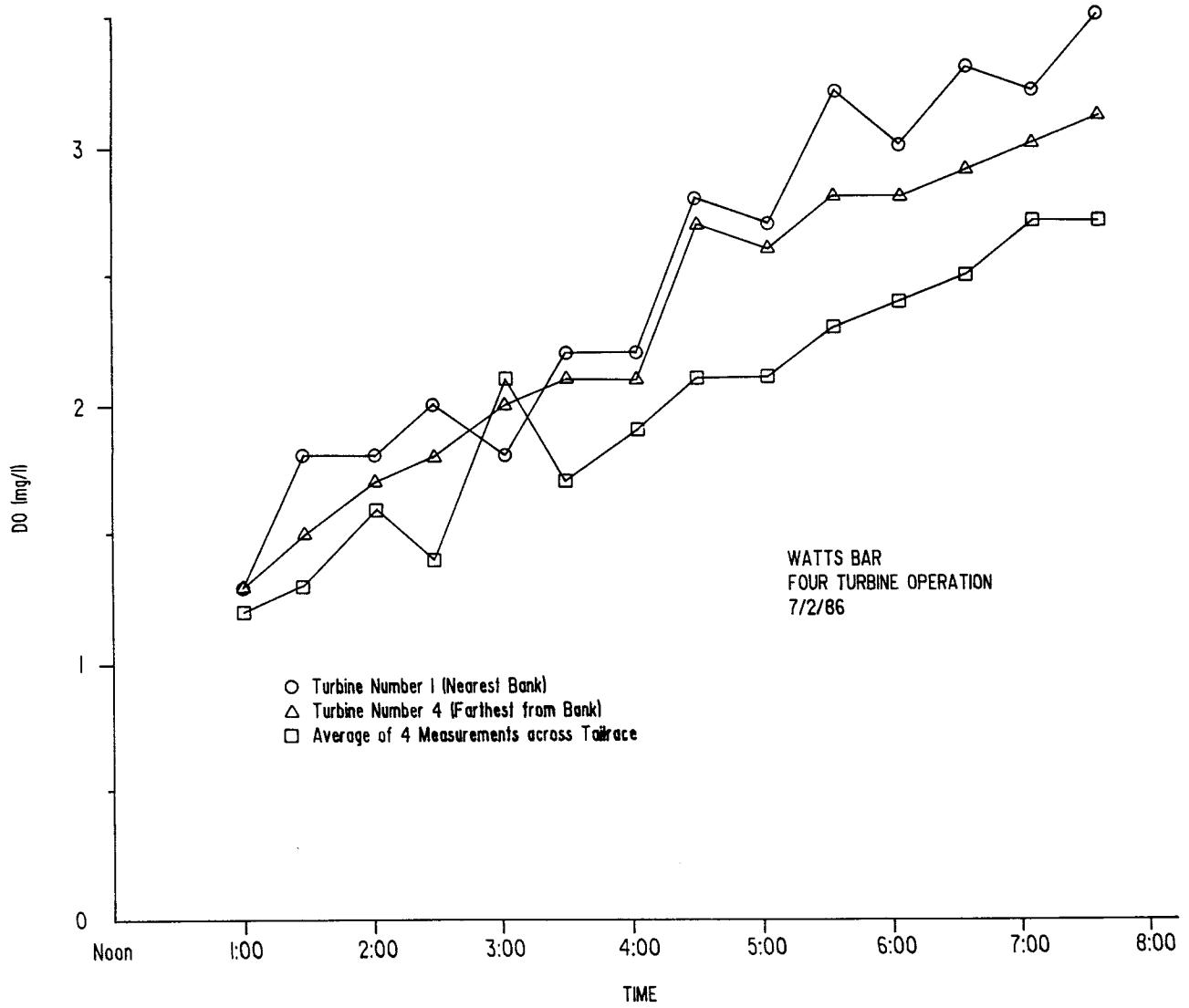


Figure 7-3. Tailrace Dissolved Oxygen after Hydroturbine Startup

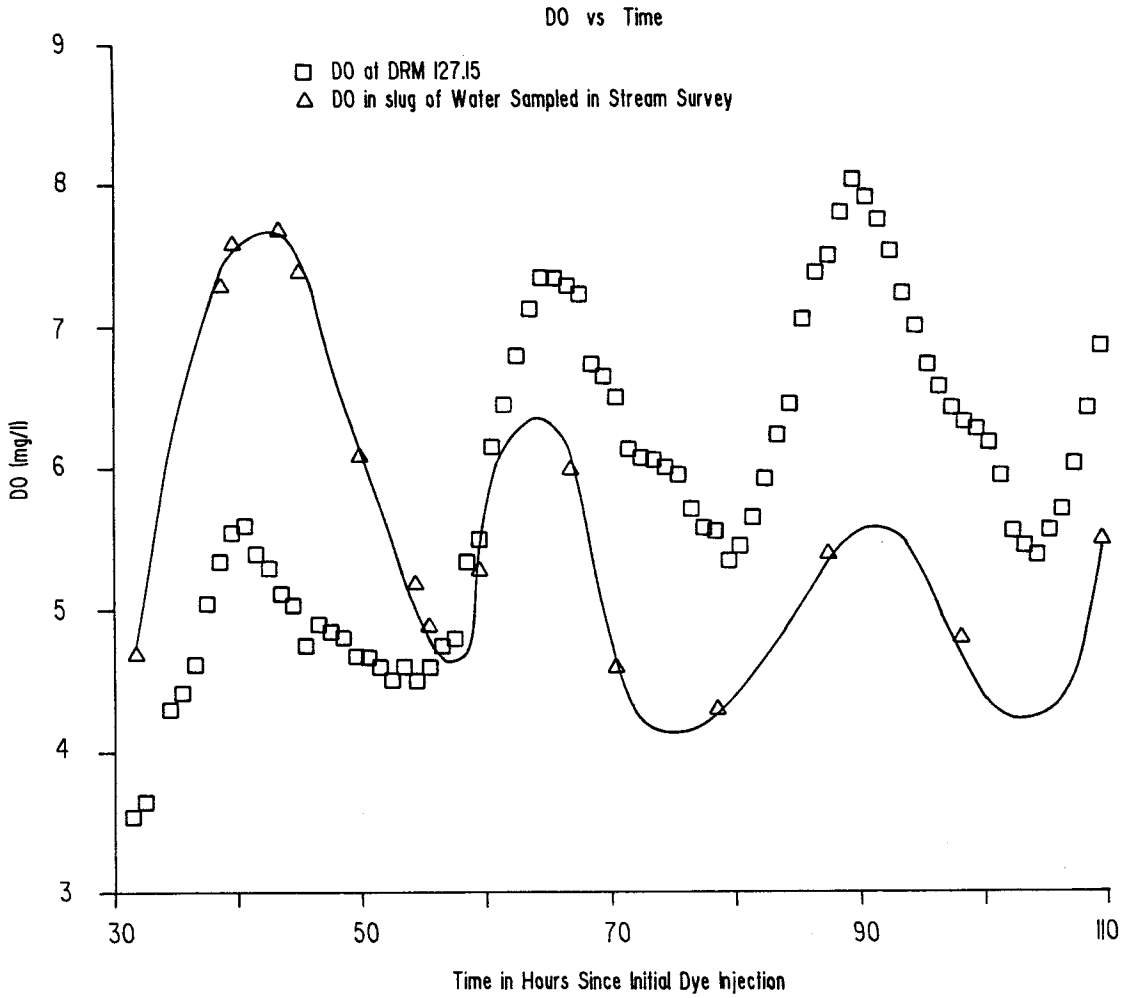


Figure 7-4. Dissolved Oxygen in the Duck River

flow can change the DO observed at a particular spot in a stream is by changing the concentration of oxygen-demanding materials.

Frequency Guidelines

Baseline Monitoring. Existing Reservoirs:
It will be important to determine seasonal variability in water quality parameters if the project involves an existing reservoir. DO and temperature data collected on monthly intervals would be adequate to determine whether the reservoir stratifies and during which part of the year any DO depletion would be most severe, but bi-weekly sampling is recommended to obtain better profiles of the reservoir and determine year-to-year variability. Often stratification and DO depletion are most severe in the summer, but other factors such as ice cover could change the time of year in which the maximum DO depletion is noted. For shallow reservoirs with short detention times, stratification might be weak and transient. It may be necessary to perform weekly sampling to detect such occurrences.

Reservoir sampling must be performed with depth. Because several parameters such as DO and temperature can be measured with probes, readings are normally taken every one to five meters, with every three meters most often being the case. The frequency of sampling at these depths for parameters that must be analyzed in a laboratory, however, would necessarily be determined by factors such as the project budget. However, the vertical variability of DO, temperature, pH, and conductivity may give some indication as to the number of samples which must be obtained for such things as BOD, nitrogen, and phosphorus.

The number of sampling locations (spacial frequency) which must be established along the reservoir length and on reservoir cross sections is highly site specific. The locations are a function of the shape of the reservoir and the location of major inlets or waste discharges. Longitudinal sampling increments of 1- to 10-miles are not uncommon. Because the water quality in the dam releases is likely to be influenced more by the water in the main body of the reservoir, lateral sampling might be confined to the old river

channel, with the embayments which lack major inflows or loadings ignored.

Tailwaters:
Baseline monitoring of a river below an existing dam is generally performed to determine both the minimum DO and the duration of the low DO period. Often the reservoir data and its interpretation provide a basis for determining when minimum levels will occur. Initially, an investigation lasting several days with samples taken hourly during turbine operation might be required to determine if the DO and temperature of the discharge vary with discharge volume or cumulative time since the hydroturbines went on-line. If the DO is stable over the course of a normal daily operating period (varying 0.5 mg/L or less), daily or even weekly grab samples over the seasonal low DO period would be sufficient to define the minimum DO for the study period. For large daily variations (greater than 0.5 mg/L), consideration should be given to continuous measurement of DO and possibly temperature.

It may also be desirable to monitor stream conditions during periods of non-discharge. In this case, DO and temperature should be measured hourly.

Monitoring could also be conducted to determine the downstream impact of the releases from the dam, particularly when site-specific standards are being considered. One method is to dye a slug of water and sample it as it moves downstream. DO, temperature, and water quality variables which can affect DO, such as BOD and nitrogen species, would be measured as the slug travels. If the slug is followed in a boat, measurements can be made every hour. If the velocity is much greater than 2 ft/sec, however, measurements should be made more frequently.

The slug of water can also be sampled at various locations from the streambank. The frequency of measurements will be determined by the rate at which the DO varies. These rates can be estimated in advance (Ref. 7-7) and the sampling frequency selected such that the DO does not change much more than 1 mg/L between measurements. Although the streambank locations are often limited by the number of access

points, a general rule of thumb is to sample the slug every mile; more locations will be required if the DO varies more than 1 mg/L per hour. Other factors which are important to the frequency of sampling include the physical characteristics of the stream, especially the location of pools and riffles.

The DO can also be monitored at one point along the river over the course of several days to determine the effect of photosynthesis and respiration. A continuous DO monitor is often used for this purpose. If discrete measurements are taken, they should be taken hourly.

Compliance And Aeration System Control

Once the seasonal and daily variation in DO are determined and the minimum DO concentration identified along with its duration, the compliance monitoring system should have a frequency which will measure significant changes in DO concentration along with the minimum value.

The objective of the compliance monitoring system is to ensure that DO is monitored during any time that it could fall below the standard established for the project. The objective of monitoring for aeration control systems is to monitor frequently enough to control the aeration system such that the DO will not fall below the standard. If DO is stable over the day (varying less than 0.5 mg/L), daily monitoring would be sufficient to control a manually operated aeration system. The greater the variation of DO, however, the higher the frequency of monitoring required. Should the daily DO variation be greater than 0.5 mg/L, several samples per day are required when the incoming DO approaches the standard. If the aeration system were to be automatically controlled, a continuous monitor would be used and the frequency of measurement would no longer be an issue.

If discrete sampling is to be conducted, operational experience or a field study would be required to determine the sampling frequency required to establish a relationship between the incoming DO and the aeration system set point. In all likelihood, continuous monitoring will most likely be less expensive and more effective than making discrete measurements several times per day.

Unless otherwise specified by the project license, a rule of thumb for the frequency of compliance measurement is that it should not be longer than that which can cause damage to the aquatic community. In the absence of other guidance and warm water species in the river, the monitoring frequency should be greater than weekly for DO in the range of 4 to 5 mg/L for unaerated water. For unaerated water with DO in the range of 3 to 4 mg/L, the monitoring frequency should be greater than daily. For DO below 3 mg/L, the monitoring frequency should be continuous. For cold water species, the ranges should be increased by 1 mg/L and possibly more during periods of critical life-form stages.

7.5 RECORDKEEPING SYSTEMS

This section is provided to make owners aware of the various levels of monitoring/recordkeeping systems. Initially, manual sampling and recording may appear to be all that is needed for DO studies. However, owners should consider the ultimate possibilities of how the data could be applied and the extent of the database generated. This is particularly true for facilities that may be considering the pursuit of site-specific standards. A sampling effort that is initiated at a very small level of effort can expand into one of considerably larger proportions. It is wise to consider such possibilities early on, and initiate a recordkeeping system that can be easily incorporated into a larger effort. Manually transferring a large record into an expanded system can be time consuming and expensive. It is also conceivable that the data may be combined with that obtained from a larger database such as STORET. Initially recording the site-specific data in a compatible format would save considerable effort in the future.

The recordkeeping system selected for archiving water quality data is controlled by several factors. First, and foremost, is the objective for storing the data. The objectives for which data are stored include (1) determining the background aquatic conditions in the area affected by the project; (2) calibrating water quality models for predicting the effect of the project on the aquatic environment; (3) analyzing aeration system performance; and (4) reporting compliance with the water quality standard.

Other factors often considered when developing a recordkeeping system are the type of instrumentation that will be used to collect the water quality data, the cost of initially storing the data, and the cost of processing the data. Due to the nature of DO sampling programs, the recordkeeping system will often become a combination of manual and automatic sampling and recording. Certain parameters (i.e., DO, flow, temperature) will require frequent sampling and recording, but can be done so automatically, while others are sampled less often, but require laboratory analysis. In cases such as these, the laboratory data can be manually added to a file that has been generated by the automatic sampling system.

Recordkeeping and Data Processing Systems

The sophistication of the recordkeeping system depends on the number of data and how the data will be processed or reported. Obviously, if one grab sample is to be taken monthly or even weekly from one location, the recordkeeping requirements will be minuscule when compared to that of a system that samples every few seconds at multiple locations. If few data are to be reported and they are to be reported in their raw form or perhaps used to calculate one or two simple statistics, the recordkeeping system required will be far less elaborate than the one needed to provide for the summarizing and plotting of thousands of data points.

Manual Systems. The lowest level of recordkeeping, manual systems, are the least complicated and will suffice for programs that will not encounter large volumes of data. Manual systems include anything from hand copying numbers into a book or table, to manually entering the data into a computer database. There are several database and spreadsheet packages commercially available which can be used on personal computers to store, analyze, and report the data in tables and figures. Figure 7-5 illustrates a typical Water Quality Data Field Sheet. Note that the following information is included:

Study name
Exact location
Personnel responsible
Parameters measured, including units
Time and date
Sample number
Weather conditions
Remarks

SURVEY:	STATE:	ACCOUNT NO.:	FIELD CREW:
STREAM:	MILEAGE:	DATE (Yr.Mo.Day)	REMARKS:
1 3 4 10 S C			Tape: / Gage: / (over)
		AIR TEMP.	WEATHER / SKY COVER: 0-1/10-1/4-1/2-3/4-9/10-10/10

Tag No.	Time ET CT	3 Depth in feet	98 Depth in meters	2 Hor. Loc. % Right Bank Looking Upstream	10 Temp °C/°F	94 Conductivity umhos/cm	300 Dis. Oxygen (mg/l)	400 pH	431 Total Alkal. mg/l as $CaCo_3$	435 Acidity mg/l as $CaCo_3$		

NOTE TO FIELD CREW: THESE DATA WILL BE KEYPUNCHED AS APPEARS; PLEASE WRITE LEGIBLY WITH PEN. DO NOT WRITE IN DEPTH (FEET) COLUMN OR COMPUTER BLOCKS.

Figure 7-5. Example of Field Water Quality Data Form

Charts, Punch Tape, And Magnetic Storage. When larger numbers of parameters are monitored, the frequency of sampling is increased, or the duration of the monitoring period is extended (i.e. several years), more elaborate recordkeeping systems should be considered. The level of recordkeeping one step beyond manual sampling and recording would be chart recorders. Figure 7-6 shows a strip chart on which DO and temperature have been recorded from a DO/temperature analyzer. The charts offer the advantage of continuous recording of data, but retain the chore of manually transferring the information into a computer system for analysis.

To eliminate the manual labor, punched tape systems became popular. Punched tape allowed data to be automatically transferred to computers for manipulation. However, rather than provide a continuous record as in the case of the charts, the tapes only record values at specified intervals. With the development of computer applications, punched tapes have become somewhat outdated, and have been replaced by systems that incorporate magnetic media for downloading to computers.

There are several levels of sophistication in storing data magnetically, but as in the case of the charts and punched tape, the method is dependent upon the monitoring/recording device. Magnetic storage can be essentially the same as a punched tape except that the data, at pre-set intervals, are automatically logged onto a magnetic storage module rather than having a code punched into a paper tape. Once logged onto the magnetic module, the information can be retrieved from the field and processed by computer.

Data Loggers, Transmission, and Computer Systems. The next level of sophistication in recordkeeping is to electronically process a signal from the monitor by a data logger or directly by a computer in real time. Data can be transmitted by a hardwire, telephone line, or satellite from the monitor to the data logger or computer facility.[1]

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[1]A data logger for this discussion is a device with an internal clock that records millivolt signals on several channels from different monitors as a function of time. A computer also has a clock, but also has the capability to translate the millivolt signals into concentration units and process and/or store the results according to a programmed algorithm.

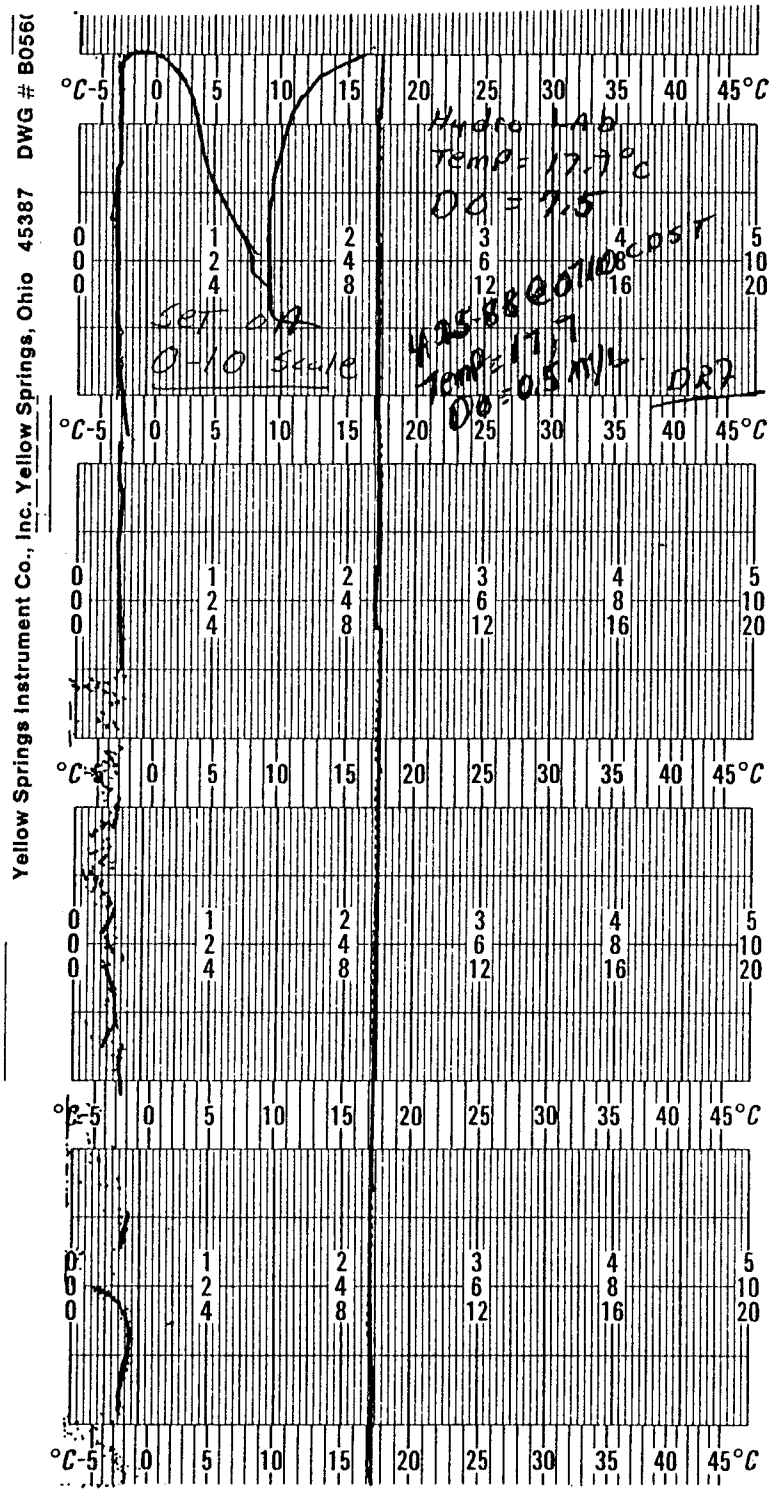


Figure 7-6. Strip Chart for DO and Temperature Recorder

An example of such a system would be for a computer to periodically sample an analog signal to the computer from a DO monitoring device, convert the signal to concentration values, and store the observed values. The sampling frequency might be intervals of a few seconds (nearly "continuous") to hours, days, or weeks. The computer would then periodically copy the data recorded to a storage device (floppy diskette, hard disk, or magnetic tape). The same computer could employ a commercial software package (database) to analyze and report the data. Often such databases are used with spreadsheet database management or statistical packages available for personal computers.

The costs for just the data management systems (water quality monitoring systems not included) would be from about $1,000 for a rudimentary system, to in excess of $6,000 for an elaborate configuration. Installation of the computer with all the cables and/or telemeter systems required to connect the water quality monitors might add from $2,000 to $20,000 for four monitors. An additional cost would be the development of the software for the site-specific application, adding $1,000 to $30,000, depending on the number of parameters to be measured, the sophistication of the output display, the complexities of the data processing algorithms, and whether programming expertise is available in-house. Spreadsheet and other data analysis packages are available for a few hundred dollars per package. It soon becomes obvious that the costs involved in a computer-based recordkeeping system are very site-specific. A computerized system at Douglas Dam (Tennessee) that monitored a number of parameters including four DO probes in the dam forebay and tailwater, cost $86,000. The data storage and management hardware and software were about one-half the cost (Ref. 7-8).

The computer hardware used for such systems can be custom designed specifically for the monitoring of the water quality data. Sometimes, however, the computer system is part of the main data logging system used for recording facility operational data. Incorporating the water quality monitoring system into the main data logging system for the power plant is advantageous because often the plant operating variables such as flow and water surface elevations are important to the analysis of the water quality data. Figure 7-7 illustrates an output of a computer based system that incorporates data loggers and

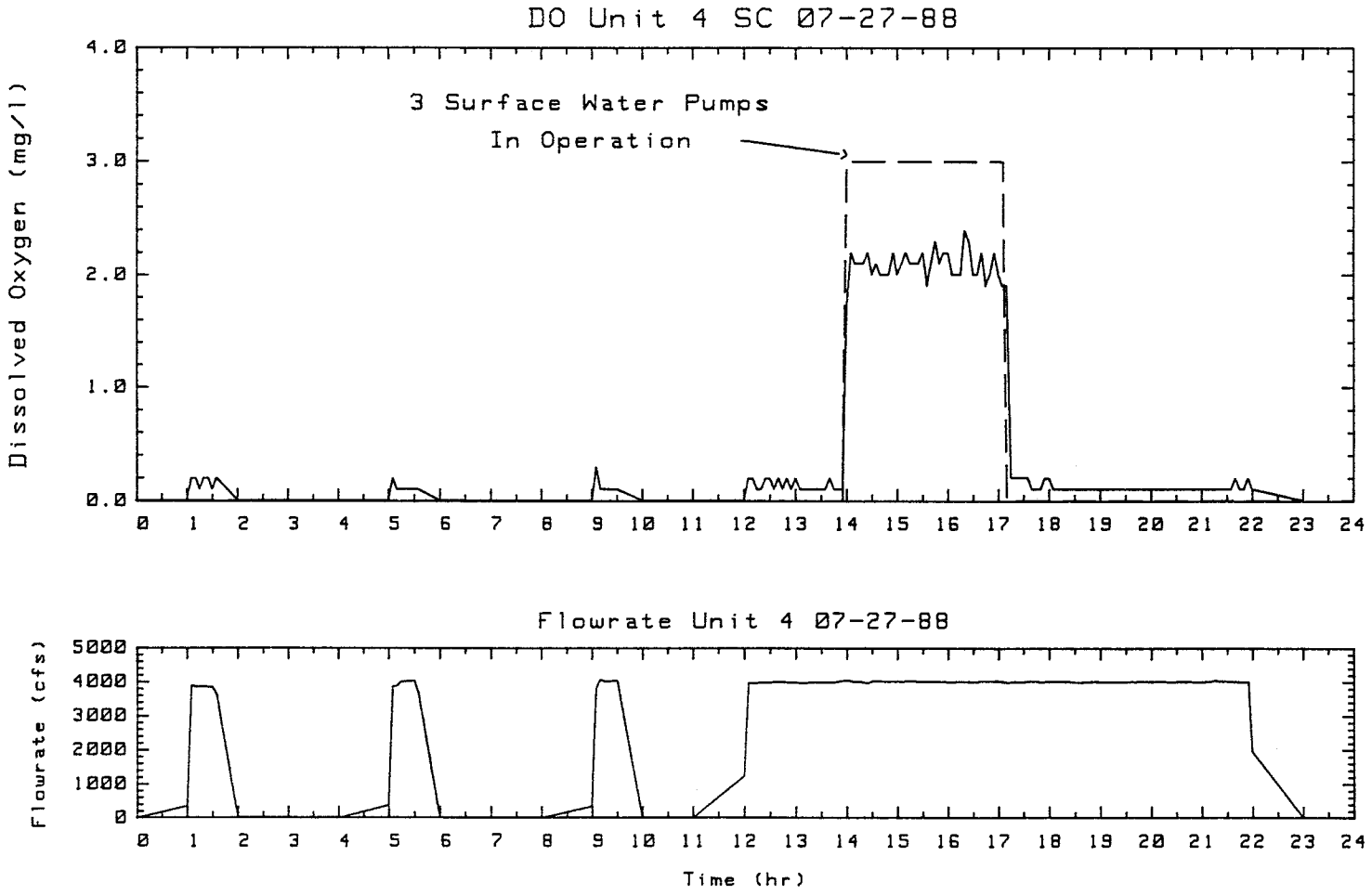


Figure 7-7. DO and Turbine Flow Plots Generated From Data Management Computer

monitors a facility's overall operations. Figure 7-8 is a photo of the equipment used to collect the data and generate the plots.

If the project is equipped with an aeration system, the computerized DO monitoring/recordkeeping system could be expanded to provide a control signal to the aeration system. The Central Nebraska Public Power and Irrigation District has a monitoring/recordkeeping system that includes a DO monitor, and is used in operating the Kingsley hydroelectric project. The computer-based monitoring system also controls the aeration system. Table 7-1 shows the elements of the monitoring system and the data which are stored (Ref. 7-9).

Uses of Data

Published Reports and Analyses. Often the hydropower owner must prepare a water quality report to be used in assessing the project's impact and/or to assist in establishing site-specific water quality standards. The number of different parameters measured in the course of the survey will result in a system of manual sampling and computerized analysis. This is generally the case because the various parameters are recorded differently. For example, data might appear on field notebooks, strip charts, data loggers, or on laboratory analyses forms. The computer analysis would likely involve routines to easily retrieve, process, and compare the data as well as just store it.

On occasion, the number of data is small and only handwritten or typed tables will be prepared from the field notes and laboratory analytical results. Even with a small amount of data, however, the trend is to prepare the reports on personal computers or automatic data processing equipment with the data in spreadsheets or tables which are magnetically stored. This form of storage will provide an easy means of combining the data with that of any future studies. Figure 7-9 shows a plot of DO and temperature with time based on discrete samples taken over a year's time. The data were stored on a computer database and then computer processed to generate the plot.

Finally, the owner may also consider using one of the large Federal and/or State databases, such as the EPA's STORET. Via the utility's computer, the owner can combine site-specific data files with the



Figure 7-8. Data Management Computer

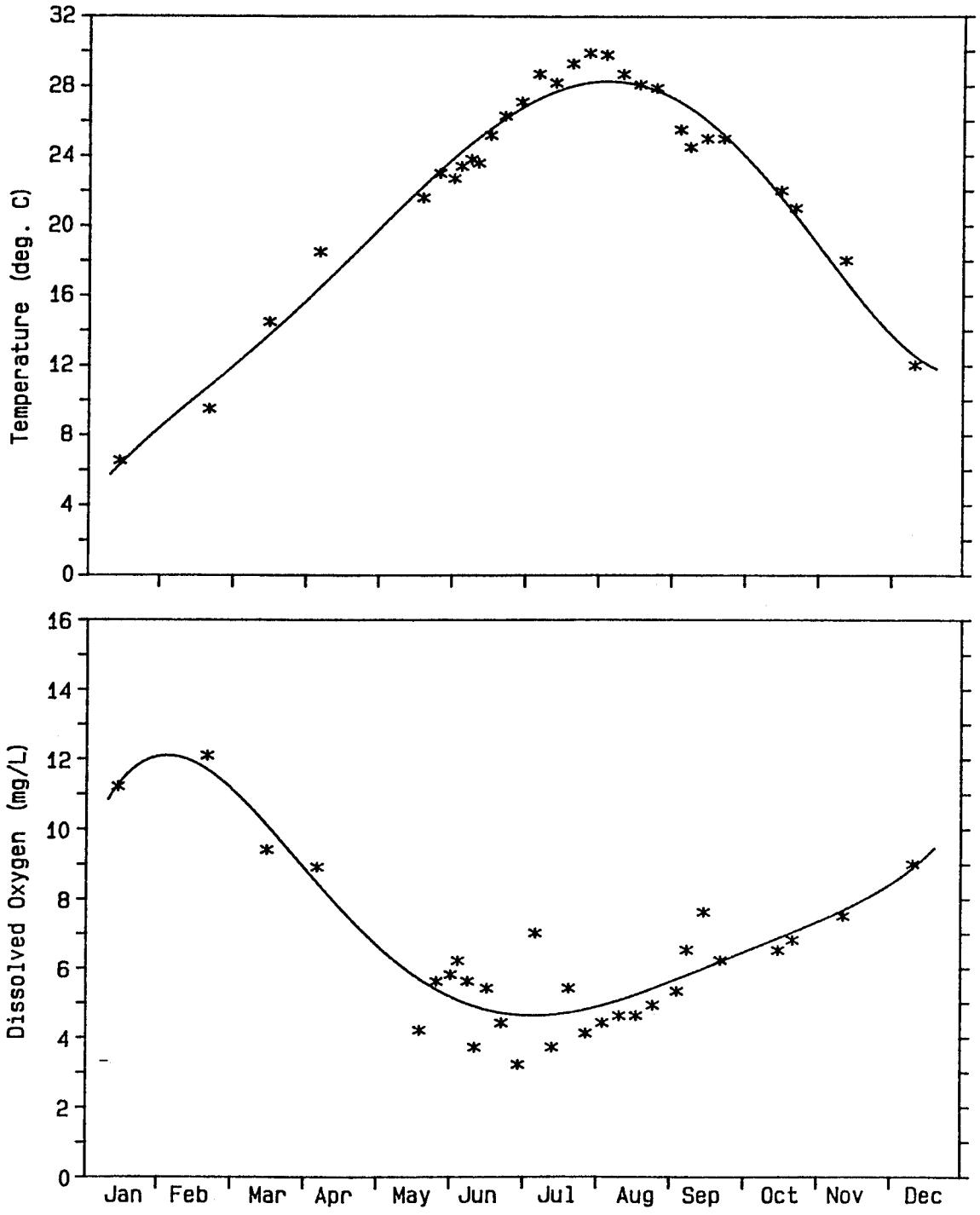


Figure 7-9. Example DO and Temperature Plots

Table 7-1

KINGSLEY HYDRO DISSOLVED OXYGEN MONITORING SYSTEM

Analog Inputs

1. Buoy line (tailrace) dissolved oxygen
2. Hydro inlet dissolved oxygen
3. Hydro inlet temperature
4. Howell-Bunger valve position
5. Hydro flow

Analog Outputs

1. Buoy line dissolved oxygen daily average
2. Buoy line dissolved oxygen seven-day average
3. Temperature daily average
4. Howell-Bunger valve flow

Digital Inputs

1. Lake McConaughy level

Description of Program Functions

The following information is stored on a hard disk when the hydro plant is operating. Data storage starts on July 1 and continues through October 15.

A. Hydro inlet dissolved oxygen at one-hour intervals
B. Buoy line dissolved oxygen at ten-minute intervals
C. Hydro inlet water temperature at one-hour intervals
D. Daily average of buoy line dissolved oxygen
E. Seven-day average of buoy line dissolved oxygen
F. Discharge through the Howell-Bunger valve

appropriate government data, and use either in-house statistical routines or the government's (which often include SAS) to analyze the files and provide formatted reports. Access to systems such as STORET generally require a User Account, which is directly available to federal and state agencies, and universities, or through the National Technical Information Service for private users. A charge for a typical STORET retrieval is likely to be less than $10. One

point to keep in mind, however, is that a user must become oriented with the procedures to access and use the various systems. This is not always a quick process, and will require expenditures of both time and money. Figure 7-10 is a typical output from STORET.

Water Quality Modeling. Quite often water quality models are used to predict the impact that the project will have on DO. Water quality models can also be used to predict the impact on the environment of mitigation and enhancement measures. If the data are being collected in large measure for the support of a water quality model, the recordkeeping system must be designed to interface with the data input needs of the model. For example, if a one-dimensional stream model such as QUAL2E is to be used, the data from one or possibly two stream surveys are not so extensive that they cannot be organized by hand and entered into the computer model. However, generally a report will be prepared which will require the preparation of tables and figures, and the data will be stored on computer for this purpose. Often some preprocessing of the data is necessary (such as averaging) before the model can use the data so putting the data into a personal computer spreadsheet is common place.

Compliance. Recordkeeping of data for easy access by models and for efficient report preparation generally involves keeping track of a number of different water quality parameters. Many of the parameters are reported in different ways, at different frequencies, for many locations, and at various times. Recordkeeping for models and report preparation can, therefore, be complex. However, recordkeeping for compliance is generally much simpler than for the previous two uses. Often the parameter list is much reduced and might include only DO and perhaps additional parameters such as flow and temperature to help interpret the DO values. Often the locations to be monitored are few in number compared with those associated with developing data for modeling, establishing baseline conditions, assessing impacts, and establishing standards.

If the required frequency is not great and only DO is to be measured, a simple manual recordkeeping system using a personal computer for storage would be sufficient. If the compliance monitoring is only

STORET RETRIEVAL DATE 89/05/03 PGM=ALLPARM PAGE: 2

017618
34 53 23.0 085 44 46.0 2
BRIDGE @ SOUTH END FLUE GAS DESULFERIZATION POND
01071 ALABAMA JACKSON
TENNESSEE RIVER BASIN 040802
/TYPA/AMBNT/STREAM UNNAMED TRIBUTARY 0.1 FORMERLY WIDOWS CR
131TVAC 871219 06030001
0000 FEET DEPTH

DATA LOCKED FOR 270 DAYS.

	INITIAL DATE			85/10/07	85/10/15	85/10/21	87/10/15	87/10/22	87/10/29	88/10/06	88/10/13	88/10/18
	INITIAL TIME						1010	1030	0940	1240	1330	1350
	MEDIUM			WATER	WATER	WATER	WATER	WATER	WATER	WATER	WATER	WATER
	DEPTH-FT(SMK)									0.983999	0.983999	0.983999
00008	LAB	IDENT.	NUMBER	22954	23371	23762	13927	14280	14697	10903		
00010	WATER	TEMP	CENT				13.1	11.5	11.8	17.0	14.5	16.2
00011	WATER	TEMP	FAHN				55.6$	52.7$	53.2$	62.6$	58.1$	61.2$
00094	CNDUCTVY	FIELD	MICROMHO				277	270	290	182	241	227
00300	DO		MG/L				8.8	8.5	8.0	8.9	9.3	8.9
00301	DO	SATUR	PERCENT				83.0$	76.6$	74.1$	91.8$	89.4$	89.0$
00400	PH		SU				7.70	7.60	7.30	6.70	7.30	7.30
00431	T ALK	FIELD	MG/L				65	85	94	86	96	100
00916	CALCIUM	CA-TOT	MG/L	47.6	49.6	47.9	41.3	45.9	54.0	41.0		
00927	MGNSIUM	MG,TOT	MG/L				10.3	10.7	11.0	5.9		
00937	PTSSIUM	K,TOT	MG/L				1.40	1.30	1.70	1.50		
00940	CHLORIDE	TOTAL	MG/L				13	13	12	4		
00945	SULFATE	SO4-TOT	MG/L	30	32	26	82	54	72	25		
01027	CADMIUM	CD,TOT	UG/L	.1K			.1K	.1K	.1K	.4		
01042	COPPER	CU,TOT	UG/L						10K	10K		
01045	IRON	FE,TOT	UG/L	340			690	100	1300	230		
01055	MANGNESE	MN	UG/L	109.0			83.0	55.0	70.0	44.0		
01092	ZINC	ZN,TOT	UG/L						10K	10K		
01105	ALUMINUM	AL,TOT	UG/L						50K	80		
01147	SELENIUM	SE,TOT	UG/L	1K			1K	1K	1K	1		
46570	CAL HARD	CA MG	MG/L				146	158	180	127		
70300	RESIDUE	DISS-180 C	MG/L	160	170	170	170	180	200	140		
74041	WQF	SAMPLE	UPDATED	871215	871215	871215	871228	871228	871228	881130	881104	881104
84068	SERIES	CODE	ALPHA	WC2A	WC2B	WC2C	WC2D	WC2E	WC2F	WC2D	WC2D	WC2D

Figure 7-10. Example of STORET Retrieval

for a short period of time, simply recording values by hand might even be the most expedient and cost effective recordkeeping system.

However, if a significant number of parameters are to be monitored, or the sampling effort is going to be conducted over a long period of time, entering the data into a database which can then be manipulated with a computer package to produce a report in a format suitable for sending to regulatory agencies will likely be worthwhile. If the compliance monitoring system is used for controlling the aeration system, the monitoring system might be sophisticated enough to incorporate data loggers and computers which can be used for storing and processing data and generating reports. If automatic control systems are not provided for the aeration system, then the cost of data loggers and data storage computers bought solely for the compliance monitoring activities must be compared to the savings in reduced labor in processing the data and in generating reports. This can only be determined on a case-by-case basis.

7.6 ADDITIONAL PARAMETERS TO MEASURE

The absolute minimum for a DO monitoring plan would be the recording of DO versus time. In some instances, this may suffice. However, rather than adopting an approach that involves the absolute minimum effort, owners should give close consideration as to what future monitoring efforts might be required. Expanding the minimum effort to include additional parameters may only slightly increase the cost, but could save considerable time and expense in the long run. The additional data could be used in the future design of efficient aeration systems, to verify effectiveness of aeration system operation, or to document site-specific changes in water quality and its effects. It is likely that at least some of the quantities listed below will be needed as the project proceeds.

Water Temperature
Discharge Flow
Total Dissolved Gas Pressure
Downstream Fishery Survey
Downstream Macro-Invertebrate Survey
Water Quality of Reservoir Inflows
Rainfall

Some of these parameters are inexpensive to monitor, while others can become extremely costly. The cost must be weighed against the possible results from obtaining the data on a site-by-site basis.

Water Temperature

Although required in many FERC licenses, water temperature should be monitored in any case. Because many DO meters incorporate temperature sensors to automatically provide accurate readings, temperature should periodically be measured independently for calibration purposes. Water temperature is also of primary importance when calculating the dissolved oxygen saturation concentration, which, in turn, correlates to the energy input required to meet state water quality standards when a deficit must be corrected. In addition, good temperature records are needed to correlate DO levels with the downstream fishery habitat.

Discharge Flow

Discharge flow is normally monitored at hydro facilities. DO data and discharge volume should be simultaneously recorded to allow for easy correlation. The data will be used to determine if and when a deficit exists, if turbine-flow and/or bypass flow affect tailrace DO levels, and, if necessary, to determine the most economical aeration system.

Total Dissolved Gas Pressure

Because several aeration techniques also result in higher levels of dissolved nitrogen, it is important to establish baseline saturation conditions. By measuring total gas pressure, temperature, and DO, dissolved nitrogen levels can be determined (Ref. 7-10). If nitrogen is near saturation, further addition via supplementary aeration systems could result in gas bubble disease and fish mortality. The final choice of aeration equipment must consider the risk of producing nitrogen supersaturation.

Downstream Fishery Survey

If the owner is seeking site-specific standards for a particular facility, a fishery survey should be conducted. The survey should identify the specific species that are present, and the various life-stages encountered. The effect on the local fishery population of

both the prevalent DO levels, and the variation, should be closely scrutinized. For example, a put-and-take fishery does not require as high a dissolved oxygen level as a body of water where naturally spawning fish occur and where early life stages of development must be protected. Fishery studies, however, must be conducted in-depth, and can be an expensive undertaking.

Downstream Macro-Invertebrate Survey

Although new to the subject of dissolved oxygen effects, TVA has begun examining the possibility of using macro-invertebrates as an overall indicator (see Section 4). Fishery surveys do well to identify the species of concern at a specific location, but may not accurately reflect the effect of low DO levels. Macro-invertebrate surveys, however, are less costly to perform, and may provide a faster, more accurate measure of the downstream effects of discharges low in DO, particularly when a facility's operation involves pulsed discharges.

Water Quality of Reservoir Inflows

Because the rate of oxygen depletion is a chemical/biological phenomena, the quality of the water entering the reservoir is an important variable that should be monitored, as a safeguard, but is often overlooked by owners. Inflows should be monitored to establish baseline conditions at the initiation of a project, and periodically sampled throughout the life of the project to detect worsening conditions. Upstream point-source contributors of excessive amounts of BOD, for example, may be detected. With proper corrective actions, such as the enforcement of state water quality standards upon these contributors, a reduction in the annual amount of aeration required in the hydro facility's discharge could be accomplished. Without periodic monitoring of reservoir inflows, a hydro facility has no way of knowing if water flowing into the reservoir is being further degraded due to changing upstream conditions. Minimally, BOD, phosphates, and nitrates should be periodically examined.

Rainfall

Rainfall and land surface are the main sources of nitrogen and phosphorous in streams and rivers (Ref. 7-11), both of which are necessary for plant growth, and which, in turn, contribute to oxygen

depletion of the hypolimnion. After studying patterns of rainfall and rates of runoff, it may be cost effective to decrease the rate of oxygen depletion by implementing measures to curb sources of non-point pollution.

When considering such options, it may be advantageous to model the reservoir and watershed to determine the role of various water sources. Rainfall would be one input for such models.

7.7 USE OF PREDICTIVE MODELS

Models provide a focal point for translating an investigator's technical knowledge into a quantitative tool where many interacting factors can be considered simultaneously. Field measurements alone may not be useful for isolating individual effects of operational changes and DO mitigation measures because of the lack of control over important environmental variables during a given field test. However, the use of models calibrated to field measurements is a powerful technique for quantifying DO responses to these changes. The modeling approach provides an understanding of DO phenomena that can pinpoint key causes and effects and suggest appropriate solutions. In many cases unnecessary expenditures for trial and error field testing can be avoided. As a word of caution, however, there is no substitute for modeler knowledge and experience in applying models and interpreting model results because of numerous inherent uncertainties in model formulation, input development, and calibration.

This section discusses elements of a responsible modeling investigation, useful applications of these tools in project assessment and mitigation, and sources of various types of models that are currently available.

Use of Models to Guide DO Mitigation Efforts

Models are particularly useful for 1) understanding the conditions that combine to create low DO in a reservoir; 2) the spatial and temporal variability of DO in the reservoir and its tailwater (i.e., exposure of the aquatic biota); and, 3) the projected effects of various management options on DO in the reservoir and its tailwater.

Improved understanding of the conditions creating low DO enables the developer to identify important influences and to properly interpret sketchy, conflicting, or counter-intuitive field data. Use of calibrated models for exploring management options can lead to cost effective solutions with less trial and error in the field. A wide range of management options can be explored with models including altered reservoir operations or withdrawal structures to blend more oxygenated surface waters into the releases, shutting off turbines in midday to allow photosynthesis to increase DO, and load reductions of point and non-point source organic and nutrient loadings.

Many more model simulations can be performed than field tests for the same cost. Models can be used effectively to screen numerous alternatives quickly, to quantify tradeoffs among promising alternatives, and to refine or optimize selected alternatives. Models are uniquely able to test alternatives under a wide range of simulated environmental conditions not controllable in prototype tests so that the true effects of certain measures can be isolated. Also, models can normally test alternatives at time and spatial scales not economically feasible in prototype tests.

Specific examples of model usage for understanding how a project affects DO and mitigating its adverse impacts are discussed in the following sections. This discussion includes both the upstream impoundment and the downstream tailwater.

Evaluating Project Effects on DO. Reservoir models require a comprehensive data collection and calibration effort, but they may be justified for certain large or controversial projects. Calibrated reservoir models can be used to quantify the extent, frequency, and timing of DO depletion in the upstream impoundment and its releases. Sensitivity of the DO problem to wet/dry hydrology and hot/cool meteorology can also be assessed. The effects of the dam and its operation on DO depletion can be examined relative to the effects of inflow loadings of nutrients, organic material, or waste heat from point and non-point sources in the watershed above the project.

Tailwater models can be used to assess the exposure of the downstream fishery and aquatic resources to spatial and temporal variations in

DO and temperature resulting from a range of upstream dam operations superimposed on the diurnal influences of instream processes. Results from these models can help identify the location, timing, and concentration of minimum DO in the tailwater under various hydrologic regimes, meteorological conditions, and inflow quality conditions. The models can show how DO recovers downstream from the dam with high, low, or unsteady dam releases. The models can show how the lowest DO in the tailwater may not always occur during generation. It may occur at a downstream location as a result of heavy plant respiration demands in the absence of compensating photosynthesis. This can occur in pre-dawn hours in reaches of heavy macrophyte growth or in long pools during low flows typical of non-generating periods. In such cases, if hydro generation is infrequent, the models may indicate that maintaining a minimum flow to continually flush these areas may be better for tailwater DO than increasing DO in the dam releases. Such wide ranging options normally have costs (particularly power losses) that could be compared with hardware options (such as turbine venting or surface pumps) for cost effectiveness.

Evaluating DO Responses to Operations and Mitigation Measures.
Reservoir models can be used to quantify reservoir and release DO under various operations, such as using outlets at different depths or blending schemes using a selective withdrawal structure. Other operational examples would be increasing or decreasing releases during certain seasons, establishment of a minimum flow through a reservoir, and modification of seasonal guide curves, such as raising or lowering the maximum pool level or extending its duration. Figure 7-11 illustrates the modelled output of three different through-flows at Ft. Loudoun Reservoir, and the resulting DO levels in the hypolimnion and the release. Figure 7-12 is the modelled results of varying the maximum pool level and its duration at Cherokee Reservoir. The plots represent simulated total reservoir volume, and the volumes of water within the reservoir that is less than 20°C, and that contains less than 3 mg/L for each simulation. In the case of simulation "4AX", the duration of the maximum pool level of the base case was extended, with little resulting effect on the volume of "cool" water, but with a considerably larger volume of water in the reservoir with a DO content less than 3 mg/L.

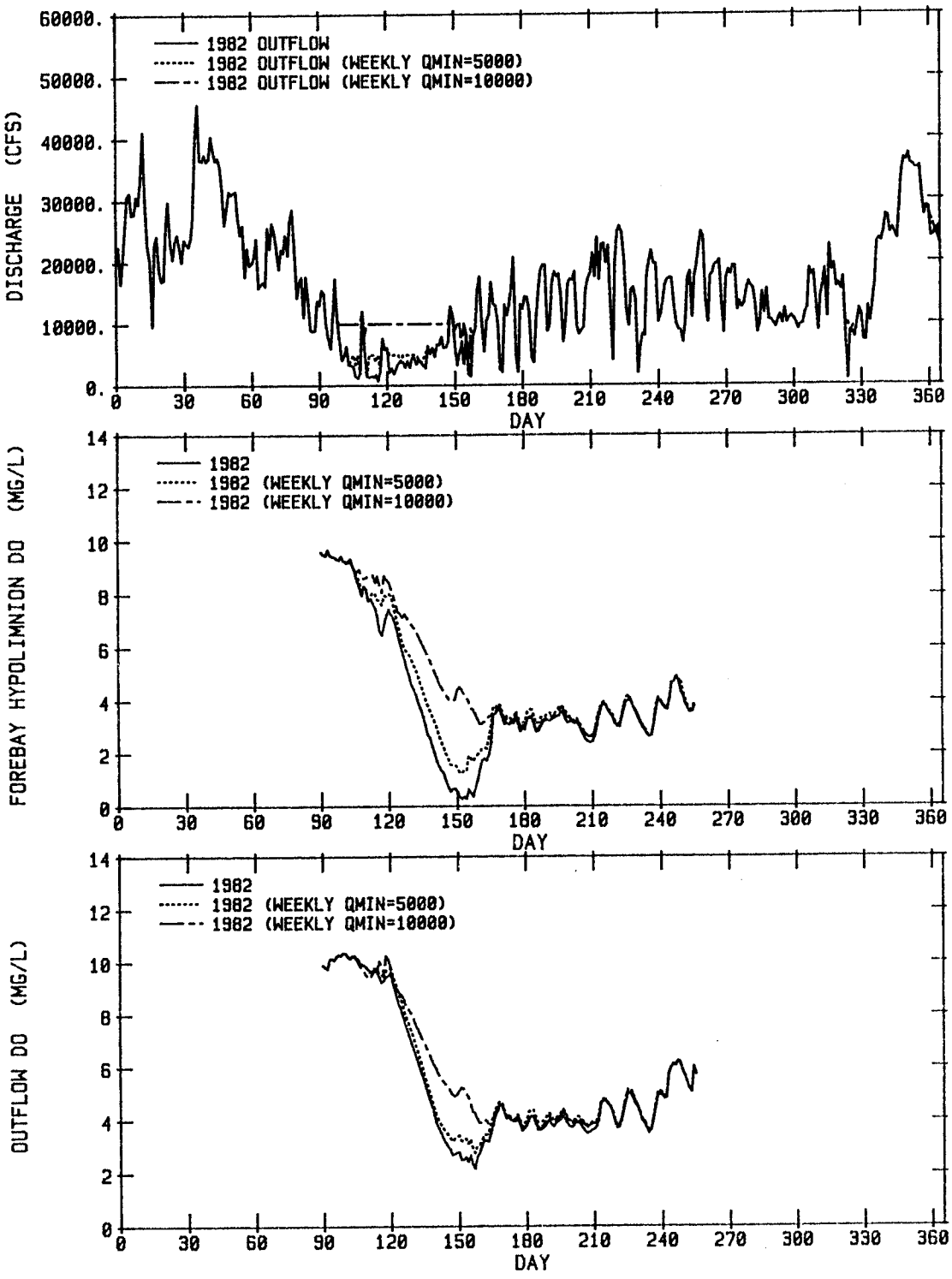


Figure 7-11. Modeled Effects of Weekly Minimum Throughflow on Ft. Loudoun Reservoir and Release DO.

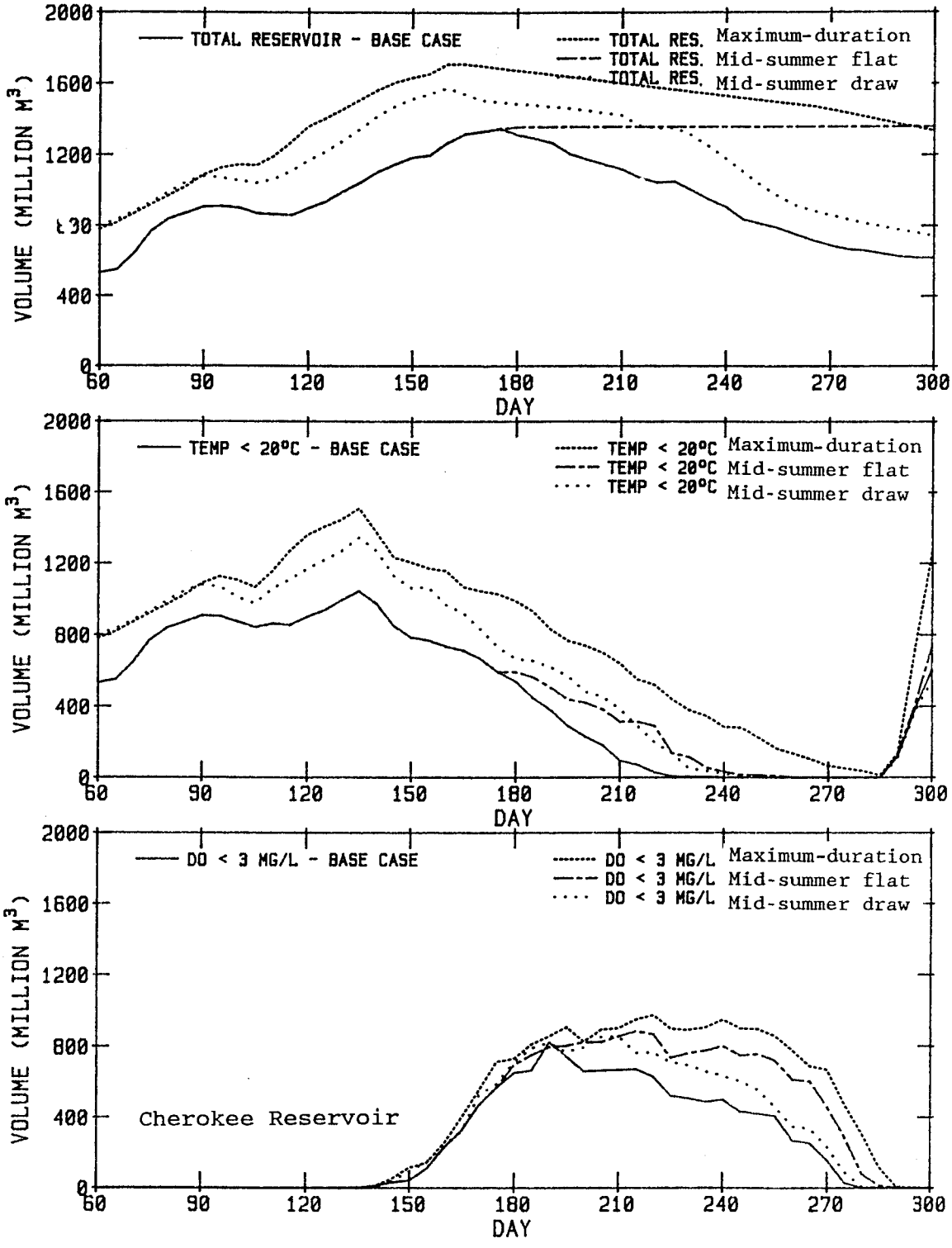


Figure 7-12. Modeled Effects of Altered Seasonal Operation on Volume of Cool Water and Low DO in Cherokee Reservoir. (Ref. 7-3)

Approximations of the effects of devices used to increase DO such as surface pumps, diffusers, and underwater obstructions (i.e., underwater dams, skimmer walls, and cutoff curtains) can also be made. The effectiveness of reducing nutrient/organic loadings versus elevating release DO by artificial means can thus be explored with reservoir models. This is well illustrated in Figure 7-13, where several different cases involving combinations of biological/chemical factors are simulated to predict the volume of water in Cherokee Reservoir that would contain less than 3 mg/L. A considerable difference is detected in the case where reservoir inflow is "clean", and sediment oxygen demand is low. The difference in this case may be significant enough to consider reservoir enhancement techniques in lieu of larger aeration systems.

Tailwater models can be used to quantify effects on DO from flow, temperature, or DO alterations at the upstream dam. A wide range of DO improvement options can be explored for cost-effectiveness, including aeration at the dam or instream at a downstream location, flow pattern changes, and reductions in waste loadings along the tailwater. Figure 7-14 models the South Fork Holston River downstream of Fort Patrick Henry Dam, and indicates the effectiveness of four different aeration approaches. Note the different degrees of influence from North Fork Creek at kilometer 14.

Refinements to aeration schemes such as aerating only during the middle of a generating period or just at the end to fill the channel with high DO water can be explored. Figure 7-15 models the interactions between operations and instream processes. Three different cases are illustrated where the turbines have been shut down for 1-, 3-, and 5-hour intervals during daylight hours to study the effect on downstream dissolved oxygen levels. In all three simulations, photosynthesis immediately causes an oxygen increase. Oxygen recovery is particularly significant in the 5-hour interval case.

Simulations can be very useful in identifying how far downstream DO improvements made at the dam will persist under various flow regimes (Figure 7-16), including generation flows, turbine pulsing schemes, and steady sluicing operations. In the case of a downstream impoundment, the mass of oxygen (flow x concentration) delivered may be more

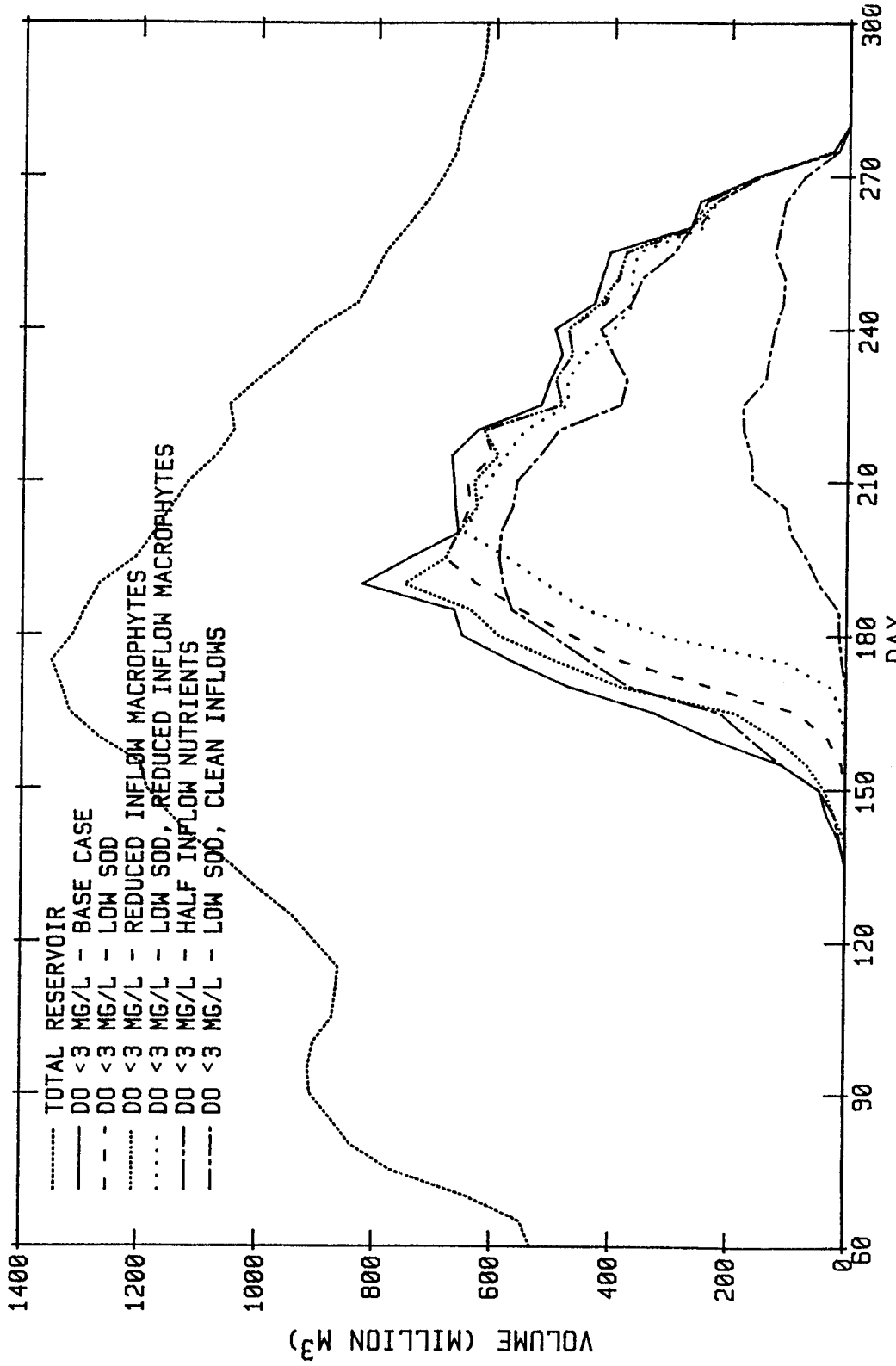


Figure 7-13. Modeled Effects of Reducing Nutrient/Organic Loadings into Cherokee Reservoir. (Ref. 7-3)

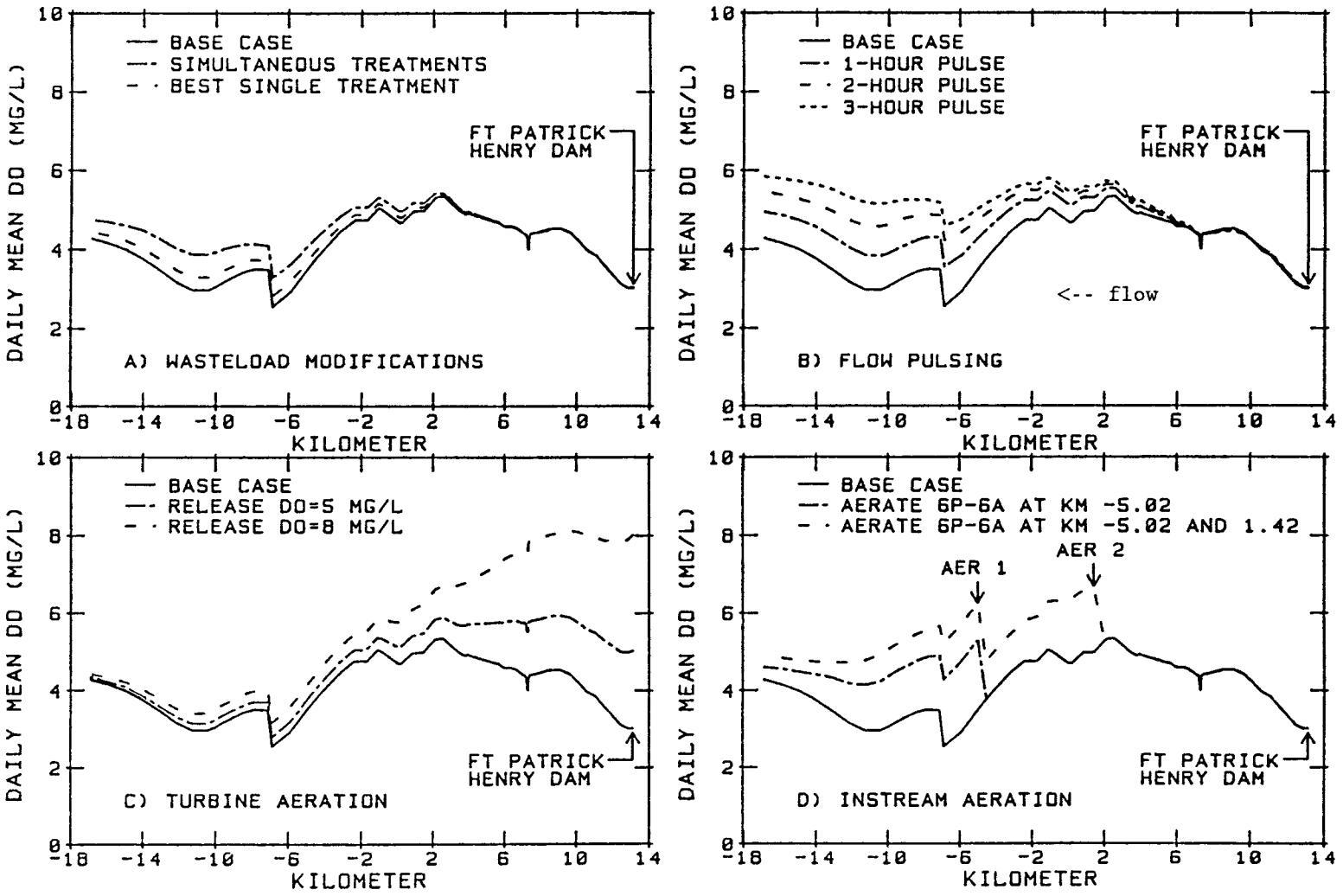
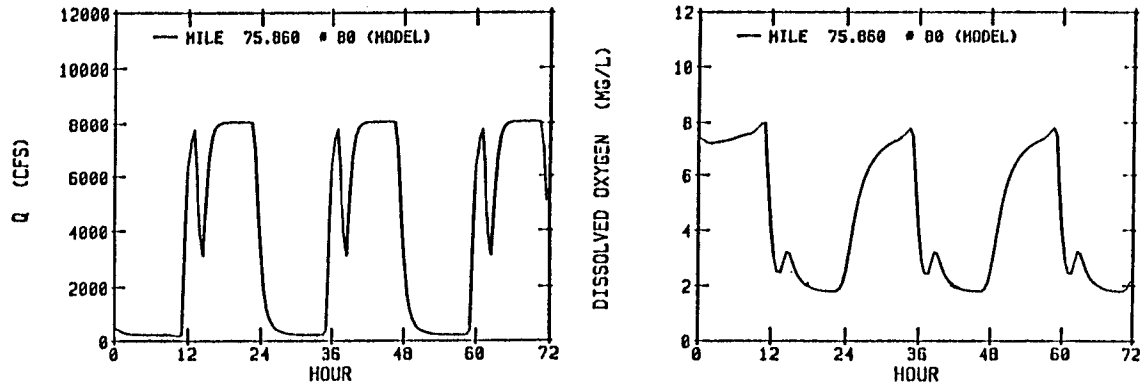
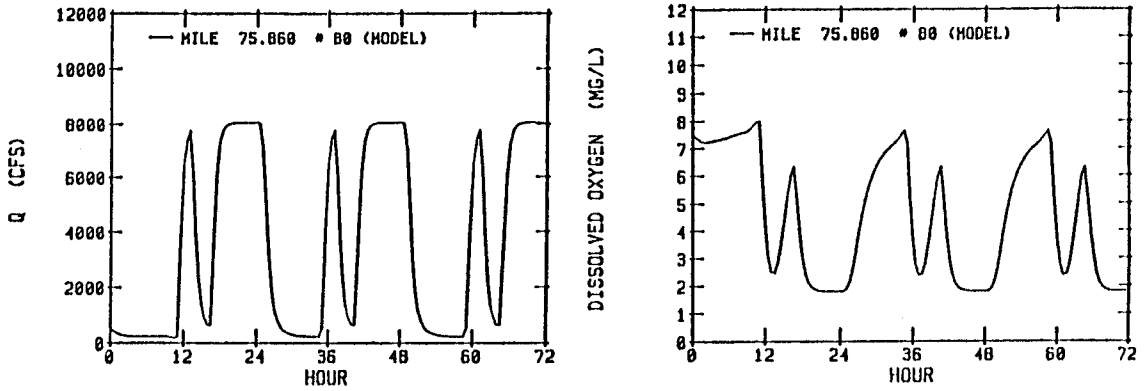


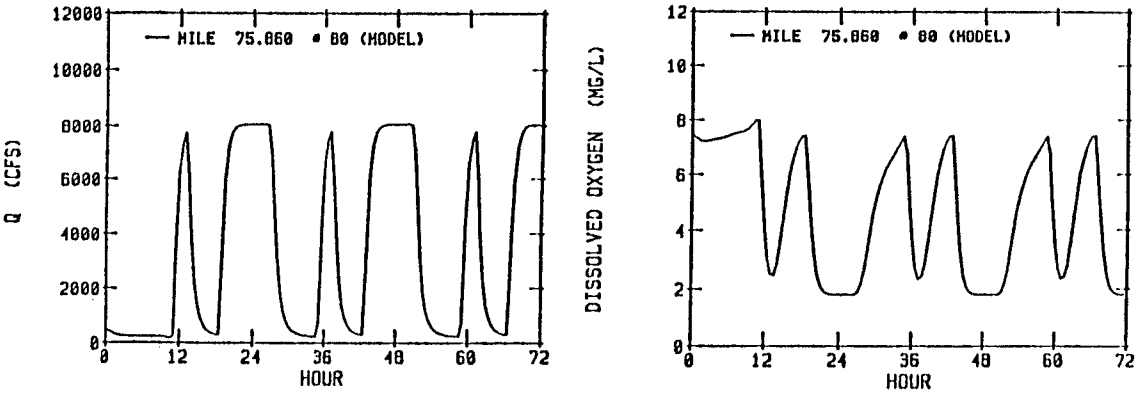
Figure 7-14. Modeled Effects of Various Improvement Strategies on Tailwater DO.



a. 1-hr turbine shutoff



b. 3-hr turbine shutoff



c. 5-hr turbine shutoff

Figure 7-15. Modeled Effects of Afternoon Turbine Shutoff and Photosynthesis on Tailwater DO. (Ref. 7-29)

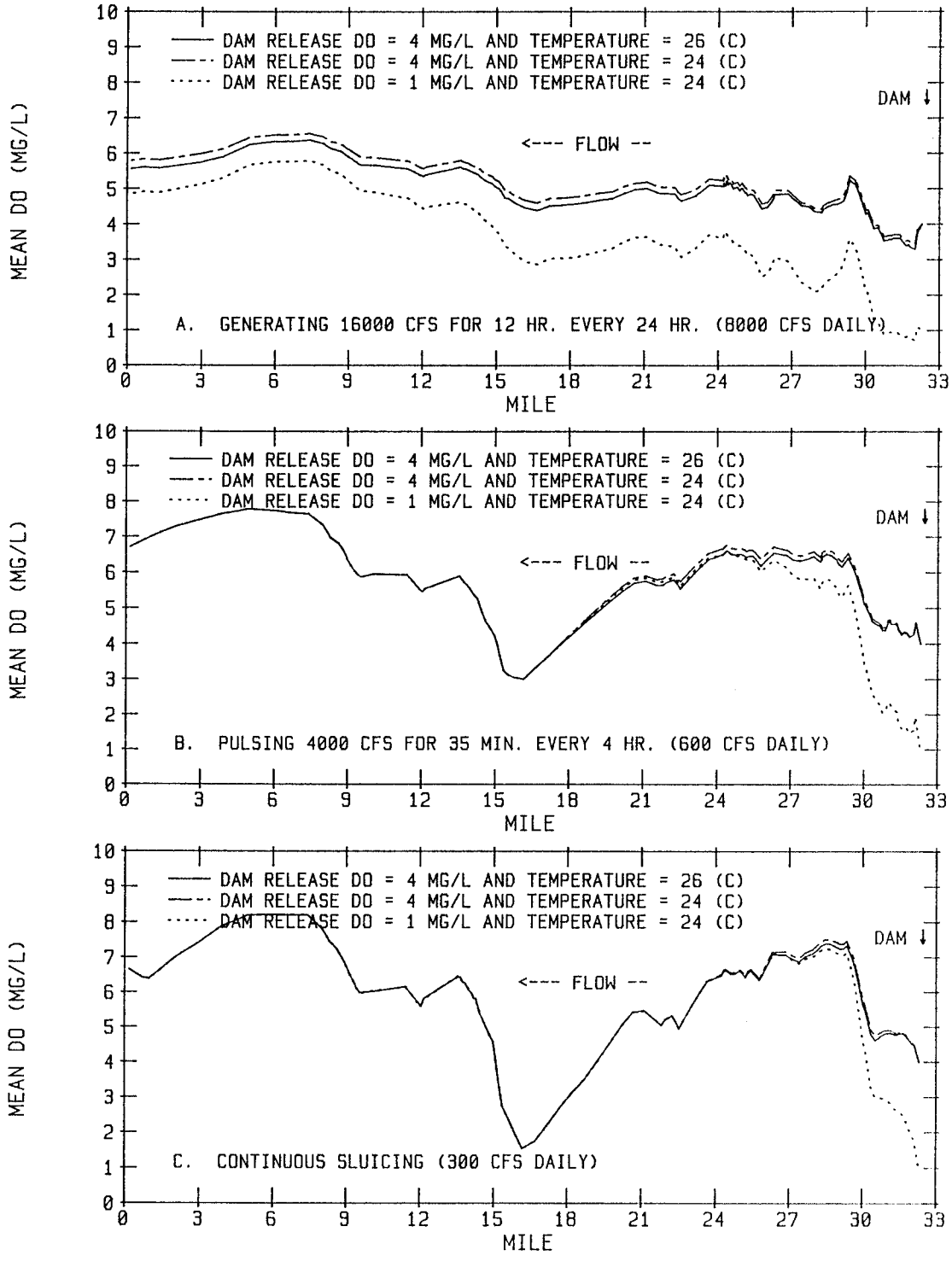


Figure 7-16. Modeled Downstream DO Improvements With and Without Dam Aeration for Various Flow Conditions. (Ref. 7-2)

important than the concentration, and this can be easily quantified with a tailwater model for various mitigative measures. In cases where the minimum DO occurs downstream rather than in the tailrace, the model may show that providing a minimum flow or some combination of minimum flow and low level of aeration may be more effective for general DO improvement than a high level of aeration at the dam.

Real Time Modeling / Monitoring Systems. Models are primarily used as diagnostic tools and for comparing alternatives. Very little literature is available on automated systems that are controlled by models in real time with the intent of maintaining a specified DO target downstream. However, some potential uses are apparent.

Many experimental studies have been made to develop quantitative expressions (i.e., model formulations) for turbine withdrawal zone and velocity profiles in the forebay of thermally stratified reservoirs (Refs. 7-12, 7-13, 7-14). When a reservoir thermally stratifies, the vertical extent of the turbine withdrawal zone is limited by the strength of the density gradient. The zone widens with higher turbine discharges (i.e., approaches the reservoir surface drawing a larger proportion of water from the surface) or with less density stratification. The velocity profile in the withdrawal zone can be computed based on turbine discharge and the forebay temperature profile. The velocity profile can then be used with the forebay DO profile to compute release DO. Low turbine discharges during stratification when the hypolimnion is depleted in DO will result in the lowest release DO and high flows that withdraw a larger proportion of surface water will increase the release DO. Such predictions could be automated to test scheduled turbine discharges each day to determine if the flows will create potential for low release DO based on current forebay temperature and DO profiles. A tailwater DO model could be run each day using a schedule of releases and measured release quality to determine if DO objectives at all downstream locations would be met. If not, the model could be used to suggest slightly altered releases (flow and/or DO).

Stochastic models may in certain cases be useful for forecasting DO concentrations. Non-stationary stochastic models can adapt to changes in average DO concentrations and can explain well over half

the daily variability in DO patterns. Huck and Farquhar (Ref. 7-15) describe how timeseries analysis might be applied to real time forecasting of water quality. Cembrowicz and Krauter (1988) propose ARIMA (auto-regressive integrated moving average) modeling for forecasting and control in German rivers where waste discharges and storm inflows are the controlling influences. A major weakness of the timeseries models is their inability to anticipate sudden changes in the daily pattern. They appear to be most useful where periodicity in the DO levels is strong and not frequently overwhelmed by aperiodic influences. They may not be useful therefore for highly variable hydro-peaking operations. Also, different models are usually needed for various seasons or months.

Elements of a DO Modeling Investigation

Defining Modeling Objectives. Early definition of key questions to be answered is critical for a successful modeling investigation. Modeling objectives should be clear, concise, and as specific as possible. Above all, however, objectives should directly reflect cost, manpower, and time constraints (i.e., be achievable) to ensure that useful results are produced in time to affect design.

Modeling objectives will sometimes guide model selection. For example, if DO predictions are needed under low flow conditions in a pool-riffle tailwater, a model that uses considerable geometric detail may be needed to accurately predict DO recovery and diurnal patterns throughout the tailwater. If the concern is DO prediction at higher flows where the channel is filled bank to bank, a model that employs simplified geometry may be sufficient.

Well-stated objectives maintain a focus on needed results once modeling is underway. The modeler can emphasize elements with greatest influence on key issues and de-emphasize less critical elements. For example, the level of modeling needed to predict DO differences between mitigation measures is often less than that needed to predict absolute DO levels. Thus, an objective to compare specific alternatives may require less modeling effort than an objective to determine a DO concentration at some location during specific conditions.

Model Selection. A broad spectrum of models from very simple to very complex can be employed to predict DO. The appropriate model depends on the nature of the question to be addressed, the required accuracy of results, available resources (cost, manpower, time, and computer), previous modeling efforts, and skill of the modeler. A model that is too simple can be inexpensive to apply but yield no useful results. A model that is too complex can be expensive to calibrate and may be overkill. All other factors being equal, applying the simplest model that will meet all the objectives will normally be the least expensive. A big variable here is the skill of the modeler with a particular model. Modeler experience can vary so dramatically that it is often the controlling factor, regardless of model complexity.

Simple models yield results that are farther removed from the real world. Thus, these models often require greater intuitive skill to interpret their results. An example is the difference between steady and unsteady models. Reservoirs and tailwaters exhibit highly unsteady flow and water quality regimes, especially in hydropower applications. Therefore, whenever a steady state model is used, inflows and water quality inputs must represent temporal averages or some other stochastic representation, resulting in a combination of input means that may never actually occur. The results are therefore sometimes difficult to interpret, requiring considerable judgment on the part of the modeler to apply the results.

Models employed for water quality assessment of hydroprojects are of two basic types: mechanistic or statistical. Mechanistic models are formulated to include as many cause-effect relationships as are known in a given problem. Mechanistic models are usually then calibrated to field data before application. Statistical models are tools developed empirically from field data wherein variables are correlated statistically. Statistical models may or may not reflect cause-effect and are normally used only within the range of data from which they were developed. These broad model types will be discussed further in a later section on model sources.

Model Inputs. Inputs required for most mechanistic water quality models are quite similar, varying mainly in the level of detail each requires. Typical model inputs include a geometrical description of

the waterbody, inflow hydrology, inflow temperature and water quality concentrations, meteorology, rates of various water quality processes, and initial values of hydraulic and water quality variables throughout the reach.

Geometrical descriptions can range from depths, surface areas, and volumes of model segments in the simpler models to detailed irregular channel cross sections (or tabulations of geometrical properties) in more complex models.

Flow rates of all significant inflows to the modeled waterbody are required, including inflow from the upstream river, major tributaries, and distributed local inflows. Water quality of each inflow is also required, including temperature, DO, and BOD (dissolved and suspended organics) in the simple kinetic formulations. These, plus nutrients, inorganic turbidity, algae, alkalinity, and pH are often required in the more complex formulations. Timeseries of these flow and quality variables are required in a dynamic water quality model if their variation is important.

Water temperature is included in most DO models, because it accelerates reactions of all processes affecting DO. DO models may require temperature as input or contain heat budget formulations for internal computation of temperature. If heat budgets are modeled, the models require meteorological data, including dry bulb and dew point air temperatures, wind speed, cloud cover, and solar radiation; and accurate physical characteristics of the waterway, including surface area changes with time or flow, orientation of the waterway to the solar path, and shading of the waterway by trees, mountains, or other light barriers.

Formulations of reaction kinetics govern the rates of internal sources and sinks of oxygen, as well as the modeled interactions between other water quality variables affecting DO. Examples of such processes include natural reaeration, sediment oxygen demand, organic decomposition, plant photosynthesis/respiration, and nitrification. Each formulation usually requires a basic reaction rate, often specified at some standard temperature.

Initial conditions define the state of the entire modeled system at the beginning of simulation. Any model parameter that varies through the simulation requires an initial value. For hydrodynamics, initial conditions include water depths or elevations and flow rates at each model node or segment. For water quality, initial conditions include concentrations of DO and other water quality variables to be simulated. Initial conditions are sometimes estimated rather than measured, and in these cases there is a time period required for the initial conditions to no longer affect the results (usually one residence time through the system). Results during this time period should be ignored or de-emphasized in the interpretation of simulation results.

Model Calibration / Verification. All models are simplifications of reality that must be compared to real data to provide confidence in model results. Calibration of a water quality model is perhaps the most critical element of the modeling process. It can also be the most time consuming. Thorough calibration is essential because once the model is calibrated, many simulations will be made with it to compare management options. It is too late to refine the calibration after simulations have begun because meaningful comparison of simulations would be confused by further model changes.

Mills, et al (Ref. 7-16) provides a good general guide for the design of field sampling efforts to calibrate mathematical models. Variables should be measured that are identical to those being modeled so that calibration can include as much direct comparison of model versus data as possible. For example, a one-dimensional tailwater DO model predicts the cross sectional average DO at a given longitudinal location. Therefore, DO for model calibration should be measured near mid-channel in the main flow (as a minimum) rather than near the bank where velocities are lower and secondary currents or eddies exist.

Calibration also requires field measurements at approximately the same time and spatial scales at which the model is expected to provide useful results. Thus, hourly calibration data is needed to enable simulation of hourly variations (seasonal data for seasonal simulations, etc.). Tailwater models usually require a few days of

hourly or sub-hourly data to capture diurnal fluctuations in DO under variable flow regimes. Reservoir models usually require a data set covering the annual cycle of the reservoir, or at least throughout the stratified period. Verification using a second set of data is desirable, especially if the calibration data set includes some rare phenomena such as drought or waste treatment plant upset. Use of a model calibrated to summer conditions may not be appropriate for winter predictions if there are seasonal biological or physical changes in the waterbody.

In addition to fine tuning the model, calibration data should be used to critically assess all inputs and formulations. The tendency to lump all calibration error into the adjustment of one or two model coefficients should be avoided. Rather, uncertainties in all inputs, field calibration data, model formulations, and rate coefficients should be recognized. Each of these should be subject to adjustment during the calibration process commensurate with its inherent uncertainty.

Recognizing the uncertainty in model inputs and avoiding use of model coefficients to account for what are really inadequacies of the inputs and formulations can result in a more meaningful balance of processes in the calibrated model. A good example of this shows up in modeling low flow hydrodynamics in shallow tailwaters. When a model severely underpredicts water surface elevation, one should avoid arbitrarily increasing channel roughness to compensate because the discrepancy is often due to a downstream hydraulic control that exists in the field but not in the model. Thus, the model geometry is inadequate and it would be improper to adjust for this with channel roughness. Another example is when a reservoir model overpredicts phosphorus in the water column. Rather than adjusting algal uptake rates or nutrient composition to remove more phosphorus, the appropriate action may be to consider how phosphorus inflow loadings were developed. The simple use of an average inflow concentration multiplied by a variable inflow may be adding too much loading to the reservoir during wet periods, accounting for the high concentrations.

Calibration of water quality models is an iterative, highly intuitive process due to the coupled nature of most model parameters. However,

it is usually most efficient to give attention to model components in the following general sequence:

1) hydrology (water budget);

2) hydrodynamics and heat budget (water surface, depths, surface areas, travel times, flow and velocity fields, mixing, thermal stratification);

3) physical processes with direct or indirect effects on DO (surface gas exchange, settling of suspended solids, light attenuation);

4) biochemical DO processes (sediment oxygen demand, organic decomposition, nitrification, algal/nutrient interactions).

Within this general framework, several calibration approaches for certain components have been employed. Measuring as many important process rates as resources permit (surface gas exchange, sediment oxygen demand, algal productivity) leaves fewer rates to adjust during calibration. In tailwater DO models, it is helpful to simulate with all processes turned off except reaeration, then add plant respiration followed by photosynthesis to gradually fit the model to data. Working from upstream to downstream is also advisable because water quality at downstream stations is the cumulative result of what has happened at upstream stations over previous time periods.

In tailwater model calibration, it is useful to collect data during controlled steady release over at least the daytime period to determine DO variations from photosynthesis unconfounded by flow variations. Conversely, DO data collected during unsteady nighttime flows will isolate the transient flow effect on DO unconfounded by photosynthesis. Sampling at pairs of stations located at a known travel time apart for diel curve analysis offers an excellent means to back calculate rates for natural reaeration, photosynthetic oxygen production, and community respiration in river models as suggested by Gulliver and Stefan (Ref.7-17).

For a proposed dam and impoundment it may be impossible to collect meaningful field data, especially for calibration of a reservoir model. In these cases, the model can often be calibrated to a nearby reservoir with similar loadings, hydrology, and reservoir morphology,

and the results used to infer conditions at the proposed site. A model can also be built using loadings, hydrology, and reservoir morphology from the proposed site with the calibration coefficients developed from modeling the nearby site. Downstream effects of operations and mitigative measures for a proposed site can normally be well predicted well with a tailwater model calibrated to pre-project conditions, assuming no channel alteration or biological changes with the proposed project. However, biological changes in the tailwater with the new project may be important and altered weed growth in the channel can have major impacts on the DO regime. Thus, even for downstream effects, it may be prudent to calibrate using data from a similar tailwater of a nearby hydroproject, and use these process coefficients in a model of the tailwater for the proposed project.

Sensitivity Simulations. Once the model is calibrated, and prior to its use for management simulations, it should be subjected to sensitivity testing whereby model coefficients and inputs are varied within the range of uncertainty and the results critically reviewed. It is valuable to learn at this point what effects these model uncertainties may have, not just on model results, but more importantly on conclusions to be drawn from the results. If model results are not sensitive to uncertain inputs, then those inputs may not require great accuracy, or perhaps may be just as well represented with a constant value. If model results are sensitive, but the conclusions would not be changed, then there still may be little need for refinements. However, if it appears that conclusions will be sensitive to model uncertainties, the model and inputs should be reformulated or refined.

Uncertainty exists in most model formulations and virtually all model inputs, including inflow hydrology, inflow quality concentrations and loadings, and meteorology. Uncertainty is especially common in unmeasured process rates and coefficients. Even when measured, some uncertainty may remain in certain rates. Weed respiration is a good example because measurements usually only apply to a short reach, but species and distribution of weeds over an entire tailwater can be highly variable.

Sensitivity simulations can also be used to explore what processes are influencing DO in the waterbody. All process rates can be set to zero, then added one by one in a series of simulations to show the effects of individual processes on DO. Synergisms between processes in the more complex models may be explored by altering the sequence of processes added in the series of simulations.

Scrutiny of model formulations, inputs, and calibration coefficients should continue throughout sensitivity simulations. Sensitivity simulations and validation simulations on new data can often enlighten the modeler to many inherent dangers of modeling. For example, it is possible for a model to be calibrated to a set of field conditions and be a poor calibration, because an improper balance of DO processes can still combine to yield the correct total oxygen demand. Worse yet, a model with an incorrect mechanistic formulation can often still be calibrated to reproduce field data for one set of conditions. Thus, when feasible, validation of the model on data collected under a different set of conditions is always prudent.

Management Simulations. The real value of a calibrated model is for use in management simulations that explore effects of projects and mitigation measures on DO patterns. Thus, simulations of alternatives are often compared to a "base case" that represents conditions without the proposed project or mitigation measure. Examples of the use of models to explore management options has been provided in the previous section.

Presentation and Reporting Model Results. Model results, presented graphically, represent an effective means of communication with resource agencies and project sponsors. Modeling demonstrates a serious intent on the part of the owner to understand the impacts of the development and to provide for a level of DO mitigation appropriate for the project. Results can illustrate the effects of both incremental changes and worst case scenarios so all interested parties can understand tradeoffs among alternatives.

Responsible reporting of model results should include uncertainty arising from model limitations. Even so, such results often represent the most definitive information available to the decision maker.

Modeling investigations can be especially effective when supported favorably by peer review from well-respected professionals knowledgeable in the field.

Sources and Types of Models

Model Sources. Reservoir and tailwater models highly suited for DO improvement investigations have been developed by federal water resource agencies involved in this work, especially by TVA Engineering Laboratory in Norris, Tennessee and Corps of Engineers Waterways Experiment Station (WES) in Vicksburg, Mississippi. The US Geological Survey (USGS) in Reston, Virginia has also developed a river water quality model suitable for tailwater DO investigations. Many complex water quality models having DO as an important output variable are distributed by the Corps of Engineers Hydrologic Engineering Center (HEC) in Davis, California and the Environmental Protection Agency Environmental Research Laboratory (EPA-Athens) in Athens, Georgia. Some are available by referral from these agencies to private vendors or universities who support their own versions of certain models.

Available models range from simple to complex. Modeling teams with experience in tailwater DO improvements at TVA and WES can provide guidance on model selection for particular applications. Experience and familiarity with a particular model is a major factor in model choice. When beginning a project with an unfamiliar model, the proximity of the model developers and their technical support can be an overriding factor.

Mechanistic Models. A mechanistic model is an assemblage of mathematical expressions that describe cause-effect relationships. Conservation of mass is a cornerstone in the simplest of these models. More complex formulations may include momentum and thermal energy balances. Model complexity also depends on whether it is steady state or dynamic; the number of spatial dimensions over which DO gradients are predicted; and the number of other state variables that are included. Reservoir models are often kinetically more complex than river models because longer residence times in reservoirs allow many slower processes to influence DO. In river models, key kinetic processes are usually fewer in number due to short travel

times, and more attention is given to robust model execution with the rapid water quality transients that must be simulated. In deep storage reservoirs exhibiting strong thermal stratification, one-dimensional vertical models such as CE-QUAL-R1 (WES) or WQRRS (HEC) may be suitable. In mainstem and transition reservoirs where important DO gradients exist in the vertical and longitudinal directions, a two-dimensional reservoir model such as BETTER (TVA) described by Shiao, et. al. (Ref.7-18), or CE-QUAL-W2 (WES) described by WES Environmental and Hydraulics Laboratories (Ref. 7-19) may be appropriate.

DO models for rivers need not be complex for all applications. Simple, informative steady state models can be built quickly in a spreadsheet format by adapting model formulations described in modeling references such as Bowie, et. al. (Ref. 7-20), Reckhow and Chapra (Ref.7-21), and Thomann (Ref. 7-7). Reasonable ranges for various process rates and other model coefficients can be obtained from Bowie, et. al. (Ref. 7-20) or from a very comprehensive summary of earlier literature by Jorgensen (Ref. 7-22). A simplified steady-state DO model is described by Martin (Ref. 7-23) and another, developed in spreadsheet format, is described by Railsback and Jager (Ref. 7-24). A widely used steady-state, one-dimensional river model that includes more complete kinetics and time-varying photosynthetic effects is QUAL2E (EPA-Athens), described by Brown and Barnwell (Ref. 7-25).

Dynamic one-dimensional river models provide an effective means for evaluating alternatives that are heavily influenced by transient flows typical of hydro-peaking operations. Examples include aerating portions of turbine generating periods or timing releases to achieve DO targets at certain downstream locations. They also can provide realistic daily averages of temporally varying phenomena under a variety of flow patterns. Dynamic models that have been used extensively by TVA and WES for tailwater DO improvement investigations are ADYN and JRQUAL (TVA), and CE-QUAL-RIV1H and -RIV1Q (WES), descendants of an earlier model described by Bedford, et al. (Ref. 7-26).

Several models exist with a shell transport structure for which the user can write or substitute his own kinetics. Examples are WASP3

(EPA-Athens), a river/reservoir model described by Ambrose, et. al. (Ref. 7-27); and BLTM (USGS), a river model described by Jobson and Schoellhamer (Ref. 7-28).

Mechanistic models result in greater understanding of DO responses to various operations and mitigation strategies. The mass balance construct underlying mechanistic models continually reminds the investigator that DO is a concentration whose value at any point in time is increasing or decreasing as a result of a quantifiable balance of competing sources and sinks of oxygen. Unlike certain statistical models, a physically-based mechanistic model also provides some justifiable basis for application beyond the ranges of data for which it was calibrated.

Cost to run these models varies considerably due both to model complexity (number of coupled state variables), modeler skill, and resolution of model (number of computational nodes and timestep size). By far the greatest expense is field data collection and model calibration. All the models listed above can be run or readily converted to run on a personal computer. Once calibrated, simulations are not overly time consuming. In fact, computerized plotting of results takes up most of the time during the simulation phase. Typically, using a personal computer (386 machine), an annual simulation of a two-dimensional reservoir normally takes 1 to 4 hours, while a typical three-day river model simulation normally takes 10 to 40 minutes. For a typical modeling investigation, the fraction of time spent on various components is roughly:

	% Modeling Budget
Defining Modeling Objectives	3
Model Selection	2
Model Input Development	10
Field Data Collection for Calibration	25
Model Calibration/Verification	40
Sensitivity Simulations	5
Management Simulations	5
Presentation and reporting model results	10
	100%

The accuracy of water quality models is highly variable, depending on complexity of model formulations, time and spatial scales, and the

calibration effort. In rough terms, the most complex dynamic reservoir models can normally be calibrated to within 2 mg/L (spatially and temporally) in the reservoir and within 0.5 to 1 mg/L in the releases. A large fraction of the solution domain of these models will be within 1 mg/L in the reservoir and 0.5 mg/L in the releases. Complex tailwater models can normally be calibrated to within 1 mg/L, with a large fraction of the solution domain within 0.5 mg/L.

Statistical Models. Statistical models can be appropriate when understanding of important physical phenomena (e.g., mixing or biochemical transformations) is so limited that it precludes development of a mechanistic model. They may also be appropriate for certain real time control applications (e.g., complex intake facilities along streams with numerous tributary inputs) where it would be infeasible to monitor all the temporally varying inputs necessary for a mechanistic model. Statistical DO models are based on regression or time-series analysis (auto-regressive) techniques.

Regression models for reservoirs often include terms with origins in the annual mass balance expressions for the reservoir, such as loadings, flushing rates, and morphometry. Reckhow and Chapra (Ref. 7-21) offer numerous constructs for such models and discuss how these can be useful for comparing DO responses across several reservoirs or for assessing DO changes at a single reservoir. Regression models for tailwaters can include key variables such as release rate, release temperature and DO, meteorology (air temperature, solar radiation, cloud cover), and distance downstream from release. Equations across tailwaters can be obtained by including channel slopes, channel morphometry, and aquatic plant indices.

Mechanistic and statistical regression models can serve complementary uses in certain applications such as developing long-term DO time-series or reconstructing incomplete records. Where long term (multi-year) simulations with a mechanistic model are impractical or too expensive, calibrated dynamic models can sometimes be used to identify key variables and produce a range of observations for a regression model. The resulting regression model can then be used to construct the long term time series. An example of this approach is described by Shiao, et al (Ref. 7-29), who has constructed a detailed 10-year

history of daily average DO and temperature in the Norris Dam tailwater with regressions based on release temperature and DO, daily release volume, and daily solar radiation. This history will be used to help explain long term trends in biological data from the tailwater.

Timeseries analysis includes auto-regressive techniques and moving average techniques. Huck and Farquhar (Ref. 7-15) describe various approaches to water quality prediction based on Box-Jenkins time-series methods. These models use values of DO (or other variables such as flow or pH) from previous hours and the previous day to make predictions into the future. The models rely on periodicity and trends in the timeseries rather than cause and effect, so they are often not sensitive enough to sudden changes resulting from aperiodic influences, such as flow transients. However, timeseries analysis for DO prediction may be suitable for certain operational systems seeking to meet compliance with downstream limits where daily or monthly averages are targeted.

7.8 AGENCY MONITORING EXPERIENCES

Federal agencies are probably the most practiced organizations at monitoring dissolved oxygen-related parameters. As part of an effort to provide owners with a better picture of the problems encountered and the current approaches to measuring DO, this section summarizes agency experiences.

Tennessee Valley Authority

TVA routinely conducts weekly, bi-weekly, or monthly field surveys at all TVA dams. The frequency of sampling depends upon the project and the time of year, but the technique is nearly always that of grab sampling. Occasionally, however, DO is monitored continuously.

The standard upon which TVA bases its DO measurements is the iodometric azide modification of the Winkler DO test (Ref. 7-30). Standard water sampling equipment, such as a Van Dorn sampler, is used to obtain samples for the Winkler determinations.

DO monitoring equipment consists of two parts: the probe, and the analyzer. The probe senses the oxygen level in the water and provides a signal to the analyzer, which electronically manipulates the signal into a more useable form. The analyzer can display/record the DO concentration, and/or can provide a signal for transmission to a central data collection point.

Although TVA has used several combinations of probes and analyzers, for the most part, the probes have been the "Clark" polarographic, membrane-covered, electrochemical sensor type, which has virtually become the standard of the industry.

Continuous DO measurements have been particularly important in conducting studies for evaluating aeration systems. Continuous DO readings of both the water upstream from the aeration system and the water in the tailrace are useful to account for DO variability before and during aeration. The tailrace monitor provides the best data for measuring DO uptake during testing. Simply measuring upstream-DO before an aeration test and downstream during the test does not sufficiently define the effectiveness of the aeration system.

When the DO equipment is operated in a continuous mode, it generally is only for a day, a few days, or a few weeks at a time. Under such conditions, the instruments are serviced daily or weekly depending upon their performance. Servicing consists of changing batteries, retrieving the data (either as strip chart recordings or magnetic storage modules), cleaning the probe, and recalibrating. It has been TVA's experience that a week between servicing is about as long as can be expected for satisfactory operation.

Most of the problems associated with TVA's efforts to monitor DO continuously have been associated with fouling of the membrane. If the polyethylene or fluorocarbon membrane is fouled, the diffusional properties are affected and error is introduced into the DO measurement.

Recently, TVA has used DO monitoring equipment in conjunction with data collection platforms (DCP) supplied by the USGS (see the section below). The platforms provide digital control, memory units, and

telemetry capability. The DCPs are programmed to operate the water quality monitors (DO, pH, temperature, and conductivity) only during periods of sampling.

A final problem that TVA has experienced with its remote continuous DO monitoring efforts include vandalism of equipment. Generally, batteries are stolen.

Case Study of Continuous DO Monitoring. TVA recently installed a continuous oxygen monitoring system at its Douglas Hydropower Plant to evaluate two aeration systems under development. The monitoring system consists of one probe suspended from a float in the forebay, two probes in flow-through cells which are supplied from the scroll-cases of the turbines, a probe suspended in a PVC stilling well mounted on a wing wall of the tailrace, and a probe approximately one-half mile downstream. In addition to a temperature probe at each sampling location, ten additional temperature probes monitor the stratification profile at ten foot intervals in the forebay. (Ref. 7-8)

Three different manufacturers'DO measuring devices are used, and none of the probes are equipped with stirring devices. The tailrace probe and the scrollcase probes do not require stirring because the water is always in motion. The probe in the forebay is of a recent design in which stirring is not required.

All of the probe analyzers are wired to a data aquisition controller, which is connected to a computer in the powerhouse. Each of the continuous DO analog signals are sampled once every seven seconds and displayed on a CRT data monitoring screen. The computer monitors a number of parameters, many of which are not related to water quality. All, or a portion of the 7-second DO samples can be saved to diskette, depending upon the programmed algorithm selected by the operator. Data on the diskettes can be read directly into Lotus spreadsheets or utilized by other software for analysis. A simple diagram of the system is shown in Figure 7-17.

One problem with the system has been fouling of the probes, particularly the forebay probe which samples at a 5-foot depth. At this

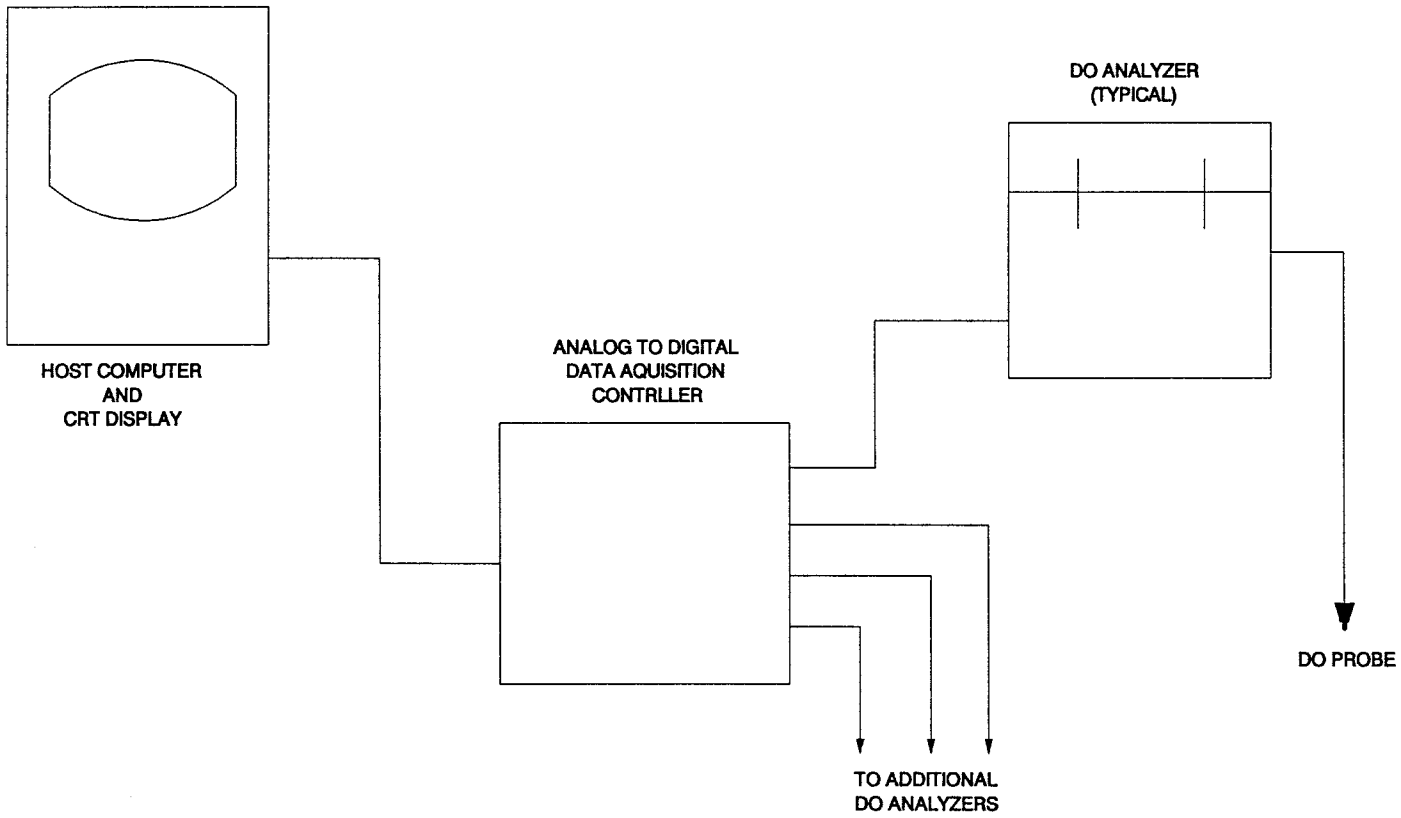


Figure 7-17. Douglas DO Monitoring System.

depth, algae growth is significant. The forebay probe requires cleaning about every two days to ensure that it functions properly. The tailrace stilling well enclosure has also suffered damage from fishermen's boats. This, in turn, has left the probe exposed and has possibly resulted in erroneous readings.

In an attempt to locate a probe that is less prone to fouling, TVA is investigating DO probes which have been used in wastewater treatment applications.

TVA has also measured total gas pressure as a part of its aeration system research and development effort. This has been done using a saturometer (Ref. 7-10). The membrane is permeable to gas molecules but blocks the water molecules. The gas pressure within the saturometer is in equilibrium with the dissolved gases in the water, and therefore, is proportional to the total dissolved gas concentration. The method is in situ but requires 15 to 30 minutes for each measurement to supply the data for calculating the total dissolved gas concentration. Because dissolved gas supersaturation has not been a problem on the TVA system, the procedure is only rarely used. (Ref. 7-8)

U.S. Geological Survey

Although DO is not a routinely monitored parameter at many of the USGS gauging and monitoring sites across the United States, the agency has experience with virtually every commercially available DO measuring device. The USGS Test Evaluation Section at the Hydrologic Instrumentation Facility (Stennis Space Center, Mississippi) evaluates the accuracy of all its DO meters on a yearly basis. In addition, the Section also evaluates DO probes and analyzers to validate the manufacturers' stated performance.

The USGS has found that probe fouling and humidity in the electronic enclosures are two of the most common problems. If DO monitoring is to be conducted under conditions in which the probe can be fouled, selecting one that is not as adversely affected by fouling as others will be important. This might involve trade-offs in relation to response time and cost. Regarding humidity problems, the USGS

suggests that the best results are achieved with instruments that have waterproof enclosures.

The agency has designed and employed its Water Quality Monitor (WQM) for sometime. The WQM is an electronic unit which controls probes for up to four different parameters and output data signals to a variety of devices. Commercial versions of the USGS's WQM are currently available. (Ref. 7-31)

U.S. Army Corps of Engineers

The Hydraulic Structures Division of Vicksburg's Waterways Experiment Station (WES) has conducted extensive research with respect to gas transfer and has considerable experience with DO and total gas measurements. WES's DO monitoring experience is similar to TVA's and USGS's experiences in that long-term continuous DO monitoring requires frequent equipment maintenance. Probe fouling was again identified as the primary problem.

Rather than use the Winkler method for calibration, WES uses an air calibration technique developed in-house, although it is somewhat similar to the air calibration method suggested by several DO analyzer manufacturers. WES's method involves the measurement of temperature, barometric pressure, and relative humidity. Air calibration has advantages over the Winkler method when interferences for the Winkler test are present in the water. The air calibration procedure is also superior to the Winkler when the personnel involved do not perform Winkler determinations regularly.

In cases where aeration is important, measurement of total gas and the determination of nitrogen supersaturation are of value, particularly when measurements are made in relation to assessing the potential for gas bubble disease in fish. WES has used both commercially available saturometers and has also developed its own electronic tensiometers for measuring total gas pressure. The newest instrument incorporates a measurement of DO, allowing nitrogen concentration to be calculated. Designs for the instrument are available from WES. (Ref. 7-32)

WES has also used a portable gas chromatograph to measure all the dissolved gases in water samples. (Ref. 7-33) The consistency of the measurements from this instrument was found to be very sensitive to instrument calibration and the skill of the operator.

The Corps' Remote Sensing Evaluation Program is presently conducting an extensive evaluation of DO monitoring equipment. The program is examining the response time, linearity, temperature compensation, and sensitivity to flow of a number of commercially available systems. A number of DO probes are also being investigated in relation to biofouling. (Ref. 7-34)

United States Bureau of Reclamation

The Bureau of Reclamation conducts many surveys using techniques and equipment similar to those of the other Federal agencies. Some hydroelectric facilities also have continuous monitoring systems, the most complete of which is found below Yellow Tail Dam, Montana.

Both DO and total dissolved gas are measured in the tailrace and at locations downstream from Yellow Tail Dam. Total gas measurements are made with a commercial saturometer which continually monitors the dissolved gas pressure using a pressure transducer. Recalibration of the DO instruments is required about every third week. DO, total gas, and temperature signals are transmitted from the probes to a commercially available data collection platform. Generally, one data point for each parameter is obtained every 15 minutes and stored over a four-hour period. At the end of each period, the data is transmitted via satellite to the Bureau's data collection centers in Billings, Montana, and Boise, Idaho. (Ref. 7-35)

7.9 ADDITIONAL SOURCES OF WATER QUALITY DATA

Although site-specific project data are preferred for project analysis, other sources of water quality data may be adequate to determine if a DO problem exists. If the data from these sources is acceptable, appreciable savings in both cost and time can be realized. Several potential sources for such data exist, depending on the location of the project. These sources include the state water resource agencies, the U.S. Geological Survey, the U.S. Environmental

Protection Agency, colleges and universities, and possibly regional conservation organizations. Normally, contacting such organizations will uncover leads to additional sources of data.

State Water Resource Agencies

Appendix A provides a listing, by state, of pertinent state agencies from which DO and other water quality information can be obtained. Generally, these agencies serve as repositories for water quality information collected in their state. In addition, the agencies can frequently assist in providing access to the EPA's STORET mainframe data base.

As discussed in Section 1, early and continuing discussions with agencies can be very beneficial. One of the initial aspects of these discussions will be the precise description of as complete a data base as necessary. In addition to the data in their own files, these agencies are knowledgeable of other water quality studies that have been conducted that would be applicable to the river project. The agencies can also advise on the reliability of the supplemental data sources.

STORET

STORET is a computerized data base utility maintained by the USEPA. It was established in the early 1960's to serve as a storage and retrieval of parametric data pertaining to the quality of the waterways within and contiguous to the United States. STORET can be accessed in several ways. A "Freedom of Information Request" made through a Freedom of Information Officer at a regional EPA office will always provide access, but may be the slowest method. NAWDEX (National Weather Data Exchange), a USGS office, is organized to respond to direct requests pertaining to STORET. For an additional fee, the National Technical Information Service (NTIS) will also perform searches. Private contractors, in certain cases are allowed direct access for related projects, as well as other state and federal agencies, and universities. Of course, EPA employees in regional offices can also access the system.

Data collected by most states and many federal and regional organizations is entered into the system and is available. This includes

USGS, the Bureau of Reclamation, and regional water quality organizations, such as ORSANCO in the Ohio River Valley. As of July, 1989, the system contained results from more than 140,000,000 analyses.

The STORET user is able to describe sampling locations by latitude/-longitude, state and country, hydraulic unit, and/or by river mile to facilitate retrieval. STORET also has the capability of storing lengthy descriptive text concerning locations or particular analyses. Data can also be processed statistically using a number of SAS (Registered trade-mark) procedures, and can be made available in machine readable format which is suitable for more custom processing such as in a water quality model. Figure 7-10 illustrates a typical printout resulting from a STORET request.

A recommended first request is for an "Inventory Summary of Available Data" which will provide information on how many sites, how much data is available (years, number of observation, etc.) and simple statistics, such as maximum and minimum, mean, and standard deviation. Such a request usually costs less than $5.00. Additional information can be obtained through the STORET User Assistance office in Washington, DC (800-424-9067). (Ref. 7-36).

U.S. Geological Survey

Another key source of information on water quantity and quality is the U.S. Geological Service (USGS). The Water Resources Division, in cooperation with state agencies, obtains a large amount of data pertaining to water resources each year. The data base, accumulated during many water years, constitutes a valuable tool for developing an improved understanding of the water resources of any given area. To make these data readily available to interested parties outside the Geological Survey, the data are published annually, by state, in a report series entitled "Water Resources Data - (state)". This report series includes records on both surface and ground water in the state. These reports can be obtained from the state office of the USGS Water Resources Division, through STORET, in paper copy, or in microfiche from the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161.

The USGS also maintains a nationwide data collection network, the National Stream Quality Accounting Network (NASQAN), to meet many of the information needs of government agencies and other groups involved in national or regional water-quality planning and management. The several hundred sites in NASQAN are generally located at the downstream ends of hydrologic accounting units designated by the U.S. Geological Survey office of Water Data Coordination in consultation with the Water Resources Council. The objective of NASQAN is to obtain information on the quality and quantity of water moving within and from the United States through a systematic and uniform process of data collection, summarization, analysis, and reporting. The design of the network is intended to provide data for (1) description of the areal variability of water quality in the Nation's rivers through analysis of data from this and other programs, (2) detection of changes or trends with time in the pattern of occurrence of water-quality characteristics, and (3) a nationally consistent data base useful for water-quality assessment and hydrologic research. Again, information on this data base, as it may apply to a specific site or project, can be obtained from the state USGS office.

Another data base, the National WATer Data STOrage and REtrieval System (WATSTORE), was established for handling water data collected through the activities of the U.S. Geological Survey and to provide for more effective and efficient means of releasing the data to the public. The system is operated and maintained on the central computer facilities of the USGS at its National Center in Reston, Virginia.

WATSTORE can provide a variety of useful products ranging from simple data tables to complex statistical analyses. A minimal fee, plus the actual computer cost incurred in producing a desired product, is charged to the requester. Information about the availability of specific types of data, the acquisition of data or products, and user charges can be obtained locally from each of the Water Resources Division's District offices.

General inquiries about WATSTORE may be directed to:

Chief Hydrologist
U.S. Geological Survey
437 National Center
Reston, Virginia 22092

U.S. Bureau of Reclamation

The United States Bureau of Reclamation's database is called HYDROMET and has been used for data storage and retrieval by not only Federal agencies but private hydroelectric companies as well. The database covers the portion of the country in which the USBR operates. Information about HYDROMET can be obtained by contacting the Bureau's regional offices in Billings, Montana, for locations east of the continental divide, or Boise, Idaho, for western locations. Data contained in HYDROMET is also available through STORET, as is generally the case with most other water quality-related databases maintained by federal and interstate agencies.

Other Sources of Information

Other sources of information may be identified when meeting with the state water quality agency, but generally these databases will be smaller and less reliable than those discussed above. Other utilities and water users (e.g., municipalities, industries, irrigation districts, etc.) and universities may possess relevant data in the form of reports, theses, environmental impact statements, or merely raw data. Leads to such information can usually be provided by the appropriate state agency. It should be reiterated, however, that all data must be qualified to the consulting agencies before it can be applied to a particular project. Minimally, the data must have been collected using the proper sampling and analyses techniques, and under very similar conditions to those of the project to be acceptable.

7.10 AVAILABLE MONITORING SCHEMES

This section provides information on available equipment for monitoring and recording DO. Manufacturers' technical and cost information, a summary of user experiences, and a general list of suppliers.

Manufacturers' Information

Thirteen manufacturers reported technical and cost information for DO monitoring systems suitable for continuous measurement. The information is summarized in Table 7-2. The less complicated monitors measure DO using a standard galvanic sensor. The reading is usually indicated on a meter, and a proportional signal is available through

Table 7-2

AVAILABLE MONITORING SYSTEMS

Manufacture and Model	Temp. Output	Power Required	Approximate Base Cost	Specified Accuracy	90 percent Response Time	Output(s) Type
Beckman 7002D	n/s	115/230 Vac	$2,395	+/- 1% F.S.	20 s	4-20mA
Capital Controls 1865	n/s	120/240 Vac	$3,000	+/- 1%	30 s	0-5V & 0-20mA
Capital Controls 1867	chart	120/240 Vac	$6,000	+/- 1%	30 s	chart recorder
Delta (Rosemount) 910	yes	115/230 Vac	$2,020	+/- 1% F.S.	20 s	4-20mA
Delta (Rosemount) 5310	yes	115/230 Vac	$1,400	+/- 1% F.S.	20 s	4-20mA
Endeco 1184	EPROM	batteries	$4,407	+/- 0.2 ppm	< 60 s	EPROM module
Endeco 1133	yes	10-20 Vdc	$2,775	+/- 0.2 ppm	< 60 s	0-5V or serial
Enterra 6320	no	110/220 Vac	$1,275	+/- 1% F.S.	n/s	0-10V & 4-20mA
Fischer & Porter 17D01000	no	120-240 Vac	$1,575	+/- 1%	30 s	4-20mA
Great Lakes - Zullig 90/5142D1	n/s	120-240 Vac	$2,875	+/- 0.3 ppm	3 s	0-5V & 4-20mA
Groundwater Technology DO-150	no	10-32 Vdc	$1,995	1.5%	40 s	0-5V & 4-20mA
Hydrolab Scout DORC	yes	+12 Vdc	$2,400	+/- 5%	n/s	RS-232 serial
Hydrolab DataSonde 2240H	yes	+12 Vdc	$3,500	+/- 2 or 5%	n/s	memory & RS-232
Leeds & Northrup 7931-20	yes	120 Vac	$1,060	+/- 1%	60 s	4-20mA
Royce (Rexnord) 9010/90	yes	115/230 Vac	$2,300	.01 mg/L	30 s	0-1V & 4-20mA
Royce (Rexnord) 9010/64	yes	115/230 Vac	$1,900	.01 mg/L	30 s	0-1V & 4-20mA
Uniloc (Rosemount) 803/430	no	115/230 Vac	$1,600	n/s	n/s	0-5V & 4-20mA
Orbisphere 2714	yes	115/220 Vac	$5,500	+/- 0.03 ppm	25 s	0-2V & 4-20mA

n/s = not specified

a recorder output port. The more complex monitors have DO sensors which impede fouling or are less sensitive to it, include temperature sensors, and have provisions for recording both DO and temperature. They are also totally submersible.

Description Of Sensors. Most sensors used with the systems in Table 7-2 are of the galvanic-type, and incorporate various techniques to reduce sensor fouling and to maintain accurate readings when low flow conditions exist near the probe. In low flow situations, the water next to the membrane becomes oxygen-deplete, resulting in erroneous readings. Stirrers and pumps can be added to reduce the chances of this occurring, but the additional equipment increases maintenance problems.

A significant problem in DO continuous monitoring is fouling of the gas-permeable membrane used on most galvanic sensors to separate the electrodes and the electrolyte from the water. Fouling reduces oxygen migration through the membrane, resulting in drift and increasing the frequency of site visits for maintenance.

Several techniques have been developed to impede fouling and to counter the effects of low flow. Some are described here, while others are discussed in the section dealing with users' experiences.

- The Zullig sensor from Great Lakes Instruments, the only sensor examined without a membrane, directly exposes the zinc/silver amalgam electrodes to the water sample, and utilizes a rotating diamond grindstone for cleaning. This resolves the fouling problem, but it requires a conductivity of at least 200 micro-Siemens per centimeter for proper operation. This is much greater than typically found in fresh water.

- The Recessed-Cathode sensor by Hydrolab reduces sensitivity to fouling and flow by recessing an increased number of cathodes from the membrane, requiring less oxygen migration through the membrane. The disadvantages of this approach is much slower response time and decreased calibration stability.

- The sensor on Endeco monitors reduces fouling and low flow effects by pulsing the probe excitation to achieve low oxygen consumption.

- A biocidal gas is released by the Royce model 90 sensor making its membrane surface unattractive to biological growth. Passive foulants such as sediments and oils, however, would still be of concern.

- The sensors on the Leeds and Northrup and the Groundwater Technology analyzers regenerate 99% of the oxygen consumed, requiring less oxygen migration through the membrane.

DO Analyzers. The analyzer converts the sensor's output to a signal capable of driving a meter and/or data recorder. The recorder, which may or may not be included in the analyzer package, can be a printer, chart recorder, data acquisition system with memory (semiconductor or disk storage), or a telemetry system. Three of the analyzers in Table 7-2 include internal data recorders, and two are completely submersible units. Completely submersible units have the added advantage of deterring vandalism. Manufacturers should be contacted for availability of models with additional features.

Analyzers With Internal Data Recorders:

- The Capital Controls 1867 also measures temperature, and includes an inkless chart recorder and calibration meter. The meter is housed in a NEMA 4X portable case.

- The Endeco 1184 is completely submersible and measures temperature. It records onto removable, reusable memory cartridges. At the maximum sampling rate of one reading per minute, the cartridge will store 11 days of readings. The cartridges must be read on an Endeco 1138 Cartridge Reader, which is interfaced to a host computer. Analysis and report software is available for an IBM personal computer running MS-DOS. The 1184 can also interface to an external telemetry system.

- The Hydrolab Datasonde 2240H can measure DO, temperature, and conductivity, and incorporates semiconductor memory. The calibration, programming, and data retrieval is via an RS-232 data port, which may also be used as a real-time output for connection to an external data recorder or telemetry system. The Datasonde is submersible, and can be equipped with a submersible battery pack. The unit is available with either the standard galvanic sensor, or the manufacturer's Recessed Cathode sensor.

Analyzers With Recorder Outputs:

- The Beckman 7002D measures only DO and has a 4-20mA current loop output. The 7002D contains a digital display for calibration and verification. The analyzer enclosure meets NEMA 3R requirements.

- The Capital Controls 1865 can measure temperature as an option, but a temperature output is not specified. The analyzer is housed in a NEMA 4X enclosure.

- The Delta model 910 analyzer with the model 921103 sensor also measures temperature. The analyzer has an LCD display for calibration and verification, and is available in a NEMA 4 case. Standard outputs for both DO and temperature are 0-10V, with 20mA current loop outputs optional.

- The Delta model 5310 analyzer with the model 921103 sensor also measures temperature. The analyzer has an analog meter for calibration and verification, and it is available in a NEMA 4 case. The standard outputs for both DO and temperature are 1-10V, with 4-20mA current loop outputs optional.

- The Endeco 1133 measures DO and temperature. However, the outputs are in the form of either a 0-5 volt analog signal or a 12-bit digital number (0-4095) via an ASCII serial data port. The conversion of the output to standard units is completed using an IBM-PC software package, which also includes a calibration routine. The software, which costs an additional $500, determines and stores the sensor's calibration curve used during conversion of the data. The Endeco 1133 is submersible.

- The Enterra 6320 measures both DO and temperature, and has a 4-20mA current loop output for DO. The analyzer is enclosed in a NEMA 4X enclosure.

- The Fischer and Porter 17DO1000 series monitor measures only DO and provides a 4-20mA current loop output. The enclosure is classified as NEMA 3.

- The Great Lakes Instruments 90 analyzer uses the Zullig 5141D1 sensor which is the only sensor examined without a membrane and is described in the previous section. The analyzer has both 4-20mA and 0-5V outputs and is enclosed in a NEMA 4X rated case.

- The Groundwater Technology DO-150 measures only DO. Output is via a 4-20mA current loop or a 0-5V analog signal. The classification of the enclosure is not specified.

- The Hydrolab Scout DORC model measures temperature, DO, conductivity, and salinity. The Scout is submersible with cables to the surface for 12VDC power and an RS-232 output. It can be programmed to output selected parameters at specified intervals or operated interactively.

- The Leeds and Northrup 7931-20 also measures temperature and outputs both DO and temperature via a 4-20mA current loop. The analyzer is housed in a NEMA 4X enclosure.

- The Royce 9010 analyzer is available with either the model 64 sensor or the model 90 sensor, and it also measures temperature. Both DO and temperature signals are available as 4-20 mA outputs. Additionally, it offers one 0-1VDC output for DO and an RS-485 digital output for hardwire transmission of data over distances much greater than that possible using an RS-232 interface. No specification is given on the enclosure.

- The Uniloc model 803 analyzer with model 430 sensor only measures DO, but does incorporate temperature compensation. Voltage (0-5V) or current loop (4-20 mA) outputs are available. The enclosure is rated NEMA 4X.

Description of Data Recorders. Because most DO analyzers do not incorporate internal data recording mechanisms, separate recording devices are necessary. Numerous data recorders or data acquisition systems (DAS) with a range of capabilities are available, including chart recorders, cassette tape data recorders, and satellite telemetry systems. One of the more common and possibly the most cost-effective approach is a microprocessor based system with semiconductor memory for data storage. This type of DAS can be programmed to acquire data at specified intervals and transfer it to a central system. Another method is to transfer the data from the DAS to a portable personal computer carried by the personnel servicing the equipment. The readings can then be evaluated on-site or transferred to a central system for plotting or statistical analysis.

User Experiences

Users of DO monitoring equipment from sixteen organizations were interviewed. Below is a brief summary of their comments.

Alabama Power. A Hydrolab Datasonde with the Clark-cell sensor has been used, but currently the recessed-cathode sensor is preferred.

Some monitoring is in eutrophic situations where excessive fouling requires cleaning of the Clark sensor every three to four days, but weekly cleaning is sufficient with the recessed-cathode sensor. In cleaner situations, bi-weekly cleaning is adequate. The recessed-cathode sensor has also been found to be more accurate in low flow situations.

A spare Datasonde allows for continuous monitoring while cleaning and calibration is performed in the laboratory. Calibration is performed in an aquarium with an air-stone bubbler at 20°C which gives 8.3 mg/L. The aquarium's concentration is verified monthly by a Winkler titration. A new installation using a Datasonde IIH with a modem and a cellular phone is being evaluated.

Augusta Waste Water Treatment Plan (Augusta, Georgia). Currently, no monitoring is being done, but in the past, a Royce analyzer with the model 90 sensor was used. The analyzer was programmed to clean the membrane fourteen minutes every four hours, and mounting of the probe was canted to allow the flow to enhance cleaning. The monitoring was successful using this approach. Calibration was performed monthly with normally less than 1% adjustment, and the membrane was replaced every six months. The Zullig probe from Great Lakes had been used, but it did not clean well in the fatty environment.

Duke Power. Duke is presently using the Hydrolab Datasonde with a Clark-cell sensor and sampling every 15 minutes over 24 hour periods. Problems were recognized with earlier Datasondes related to the temperature compensation circuitry, but this has been resolved. Calibration is performed by a Winkler titration. Duke has found Winkler titration superior to air calibration.

Commonwealth Edison. An Orbisphere analyzer with output to a strip-chart recorder is used. Cleaning and air calibration is performed weekly. A Rexnord (now Royce) and an L&N have been used. Both gave slow response time, which resulted in long start-up times (approximately 2 hours), and both seemed particularly insensitive to decreasing DO.

Dames and Moore. Dames and Moore have used various configurations of the Hydrolab Datasonde. Problems were experienced in calibration of earlier models. Problems were related to drifting and insensitive to change (slow response), but these problems have been resolved in the newer Datasondes. A Datasonde is programmed to sample every 15 minutes. Weekly, it is replaced with a clean, calibrated unit. The data from the removed unit is downloaded into a computer. The membrane is then replaced and is immersed in water several hours (preferably overnight) prior to recalibration. For more critical installations, the monitor is checked every weekday. Biological growth on the membranes has occurred, even in medium flow situations. To deter it, the Datasondes have been installed in vertically mounted pipes with holes below the sensors to allow flow. This protects the Datasonde and blocks the sunlight which promotes biological growth.

Idaho Power. Monitoring is currently performed with two different systems. One uses a Yellow Springs Instrument Company (YSI) sensor and analyzer with the owner's data recording system, and the other system is a Hydrolab Datasonde (Clark-cell) from which the data is downloaded to a computer. Both systems sample every 10 minutes. The probes are cleaned weekly and calibrated bi-weekly. The recessed-cathode sensor has not been used due to reservations concerning slow response times.

Knoxville Utilities Board (Knoxville, Tennessee). A Solomat (Stamford, CT) monitoring system is used to sample over 24 hour periods. YSI meters are used for attended (grab) sampling.

City of Loudon Waste Treatment Plant (Loudon, Tennessee). To continuously monitor the treatment plan effluent, a Zullig probe with a Great Lakes Instruments analyzer is used. The output of the analyzer is connected to a stripchart recorder. This system has performed well. Calibration is checked daily by comparing with a portable DO prob,;and adjustment is required every two or three days. The probe is removed and cleaned monthly.

RMC Environmental Services (contracted by Philadelphia Electric). Systems, including sensors, analyzer, and a Synergetics data collection platform (DCP), are configured in conjunction with the USGS.

The DCP has both telephone modem and satellite transmitter for telemetry. Calibration is checked and the probe is cleaned daily; the sensor membrane is replaced monthly.

South Florida Water Management. An Endeco model 1130 analyzer interfaced to a Omnidata Easylog (EPROM) datalogger has been quite successful. The Endeco is described as "user friendly and robust". Creeks with low flows containing much organic material are being monitored. The probes are cleaned weekly, and although they are usually dirty after a week, the readings are good. Calibrations are performed as determined by reviewing the data.

Sun Oil Company. A Royce unit is used for continuous monitoring of plant effluent. The probe is cleaned daily due to solids accumulation. An Orion sensor/analyzer is used in the lab.

State of Tennessee. YSI probes are used for attended sampling, and Hydrolab equipment is used for continuous monitoring. Low drifts have been noticed with the Hydrolab units, even in stable environments. Weekly site visits are made for cleaning and calibration checks, as a minimum.

U.S. Army Corps of Engineers. The COE is currently testing sensors and analyzers from fourteen manufacturers. Results of the test are not available at this time, but are to be summarized in a COE Engineering Technical Letter (ETL) by summer, 1989. The test includes ratings on sensitivity to flow, temperature compensation, linearity, and response time, as well as the results of field testing.

U.S. Bureau of Reclamation (Denver, Colorado). Hydrolab Datasonde (Clark-cell sensor), Hydrolab Scout (recessed-cathode sensor), and Leeds & Northrup (L&N) monitors have been used. The L&N has been more satisfactory than the Hydrolab units. The latter tend to drift more and foul excessively. Drift of up to 0.5 mg/L over five days has been measured with the Hydrolabs, where the L&Ns have drifted 1 mg/L over 30 days, after an initial drift the first day. With the two side-by-side, after three weeks the Datasonde membrane was fouled and the L&N was much cleaner. The only problem experienced with the L&N has been slow response. The L&N probes have required replacement

about every two years. Monitoring systems are cleaned and calibrated every three weeks.

U.S. Fish & Wildlife Service. The Service uses a number of sensors and analyzers throughout their hatchery and fishery research facilities. YSI is generally used for attended (grab) sampling. Poor performance in the form of drift and repeatability has resulted in L&N systems to be discarded. A newer model by Ingold Electrodes, has met with good success. After initial calibration, two of these units have performed continuously for six and nine months, respectively, at two different sites. During that time, neither unit has required calibration (checked against a Winkler titration), and original membranes remain unfouled. The manufacturer considers the membranes "low maintenance, but replaceable".

Tennessee Valley Authority. Beckman, Monitek, YSI, USGS Minimonitor, and various Hydrolab monitors have been used in the lab and in the field by TVA. Problems with drifting (up to 3.5 mg/L per week) have been experienced with the Beckman. Some problems with drifting have also been recognized with the Monitek. YSI's have work well for TVA, provided the units are cleaned and re-calibrated weekly, and membranes are replaced every third week. Various types of Hydrolab monitors have also worked well for TVA, although the recessed-cathode sensors have not been used.

Sources of DO Monitoring Hardware

Sources of DO sensors and analyzers:

Beckman Industrial Corp.
600 S. Harbor Boulevard
La Habra, CA 90631
(213) 690-7600

Capital Controls Co.
3000 Advance Lane
Colmar, PA 18915-0211
(800) 523-2553

Delta - Rosemount Analytical Division
250 Marcus Boulevard
Hauppauge, NY 11788
(516) 273-6190

Endeco Inc.
13 Atlantis Drive
Marion, MA 02738-9970
(617) 748-0366

Enterra Instrumentation Technologies
251-E Welsh Pool Road
Exton, PA 19431
(215) 363-5450

Fischer & Porter Company
Warminster, PA 18974
(215) 674-6000

Great Lakes Instruments
8855 North 55th Street
Milwaukee, WI 53223
(414) 355-8346

Groundwater Technology
4 Mill Street
Greenville, NH
(603) 878-2500

Hydrolab Corp.
PO Box 50116
Austin, TX 78763
(512) 255-8841

Ingold Electrodes, Inc.
261 Ballardvale Street
Wilmington, MA 01887
(800) 352-8763

Leeds & Northrup
Sumneytown Pike
North Wales, PA 19454
(215) 643-2000

Monitek, Inc.
1495 Zephyr Avenue
Hayward, CA 94544
(415) 471-8300

Orbisphere Laboratories
287 Lackawanna Avenue
West Patterson, NJ 07424
(201) 387-7788

Royce Instrument Corp.
13555 Gentilly Road
New Orleans, LA 70129
(504) 254-8888

Uniloc - Rosemount Analytical Division
2400 Barranca Parkway
Irvine, CA 92714
(714) 863-1181

Yellow Springs Instruments
Yellow Springs, OH 45387
(800) 343-HELP

Sources of data recording equipment:

Campbell Scientific, Inc.
PO Box 551
Logan, UT 84321
(801) 753-2342

Chessel Corp.
One Pleasant Run
Newtown, PA 18940
(215) 968-0660

Digitec Corp.
959 Cherry Avenue
Marion, OH 43302
(614) 387-3444

Keithley Instruments, Inc.
28775 Aurora Road
Cleveland, OH 44139
(216) 248-0400

Telog Instruments Inc.
2 Drumlin Square
West Henrietta, NY 14586
(716) 359-1110

Western Graphtec
11 Vanderbilt
Irvine, CA 92718-2067
(714) 770-6010

Section 8

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G-9 Colt, John, 1984. Computation of Dissolved Gas Concentrations in Water as Functions of Temperature, Salinity and Pressure. American Fisheries Society, Special Publication #14, Bethesda, Maryland.

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G-11 Oberg, Eric, Franklin D. Jones and Holbrook L. Horton, 1975. Machinery's Handbook. Industrial Press, Inc., 20th Edition.

Appendix A

AGENCY CONTACT LIST

The following list provides the names, addresses, and telephone numbers of the major state and federal agencies that have jurisdiction over a facility's discharge water quality. The lead agency in each state has administrative authority on matters related to water quality. Fish and Game, and other agencies with particular interest in water quality are also presented.

Alabama

State Agencies:

Lead:
Alabama Department of Environmental Management (ADEM)
Water Division
1751 W.L. Dickinson Dr.
Montgomery, Alabama 36130

(205) 271-7700

Additional:
Department of Conservation & Natural Resources
Division of Game & Fish
64 N. Union Street
Montgomery, Alabama 36130

(205) 261-3486

Department of Conservation & Natural Resources
Division of Marine Resources
64 N. Union Street
Montgomery, Alabama 36130

Comments:
- NPDES permit program fully approved
- state pretreatment program approved

USFWS:
Director
75 Spring Street, SW
Atlanta, Georgia 30303
(404) 221-3594

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer Dist.
P.O. Box 2288
Mobile, Alabama 36628
Attn: SAMOP-S
(205) 890-2660

EPA:
Region IV
Environmental Impact Review Offcr.
Environmental Protection Agency
345 Courtland Street, N.E.
Atlanta, Georgia 30308
(404) 257-4727

Alaska

State Agencies:

Lead:
Department of Environmental Conservation (DEC)
Division of Environmental Quality
3220 Hospital Drive Pouch 0
Juneau, Alaska 99811-1800

(907) 465-2653

Additional:
Department of Fish & Game
P.O. Box 3-2000
Juneau, Alaska 99802

(907) 465-4100

Comments:

- 3 permit information centers in Juneau, Anchorage and Fairbanks:

  Juneau (907) 465-2615
  Anchorage (907) 279-0254
  Fairbanks (907) 452-1714
  OR (907) 452-2340

- Alaska has not assumed delegation of the federal discharge permitting or pretreatment programs

- review and certification of federal NPDES permits

USFWS:
Assistant Director
1011 Tudor Road
Anchorage, Alaska 99503
(907) 263-3542

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer Dist.
P.O. Box 7002
Anchorage, Alaska 99510
Attn: NPACO-RF
(907) 752-4942

EPA:
Region X
Environmental Impact Review Officer
Environmental Protection Agency
1200 Sixth Avenue
Seattle, Washington 98101
(206) 442-1760

Arizona

State Agencies:

Lead:
Department of Environmental Quality
Waste and Water Quality Management Control
Palm Plaza Building
2005 N. Central Avenue
Phoenix, Arizona 85007

(602) 257-2305
(602) 262-8012
(24 hr in-State numbers)

Additional:
Game & Fish Department
2222 W. Greenway Road
Phoenix, Arizona 85023

(602) 942-3000

Comments:
- ♦ does not have full authority to manage the federal NPDES or pretreatment provisions
- ♦ administers substantial portions
- ♦ working on legislation to gain full delegation of NPDES

USFWS:
Director
500 Gold Avenue SW.
Albuquerque, New Mexico 87103
(505) 474-2321

EPA:
Region IX
Environmental Impact Review Officer
Environmental Protection Agency
215 Fremont Street
San Francisco, California 94105
(415) 556-2320

Arkansas

State Agencies:

Lead:
Department of Pollution
Control and Ecology (DPCE)
Water Division
8001 National Drive
Little Rock, Arkansas 72209

(501) 562-7444

Comments:
- authority to manage federal NPDES program
- authority to manage pretreatment program

Additional:
Game & Fish Commission
#2 Natural Resources Dr.
Little Rock, AR 72205

(501) 223-6300

USFWS:
Director
75 Spring Street
Atlanta, Georgia 30303
(404) 221-3594

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer Dist.
P.O. Box 867
Little Rock, AR 72203
Attn: SWLCO-D

(501) 378-5296

EPA:
Region VI
Environmental Impact Review Officer
Environmental Protection Agency
First International Building
1201 Elm Street
Dallas, Texas 75270

California

State Agencies:

Lead:
California Water Resources
Control Board
P.O. Box 100
901 P Street
Sacramento, California 95801

(916) 322-3132

Additional:
Department of Water Resources
1416 Ninth Street
Sacramento, California 95814

(916) 445-9248

California Water Commission
1416 Ninth Street, Rm. 1104-4
Sacramento, California 95814

(916) 445-8750

Department of Fish & Game
1416 Ninth Street
Sacramento, California 95814

(916) 445-3531

Fish & Game Commission
1416 Ninth Street
Sacramento, California 95814

(916) 445-5708

California Coastal Commission
631 Howard Street
San Francisco, CA 94105

(415) 543-8555

Comments:

- federal delegation of the NPDES permit program
- applications must be submitted to the appropriate regional board
- California does not have a federally approved pretreatment program

FERC:
San Francisco Regional Office
333 Market Street
6th Floor
San Francisco, California 94105
(415) 974-7150

USFWS:
Director
500 N.E. Multonomah St.
Portland, Oregon 97232
(503) 231-6118

CORP OF ENGINEERS:

The District Engineer
U.S. Army Engineer District
P.O. Box 2711
Los Angeles, California 90053
Attn: SPLCO-N
(213) 688-5607

San Francisco
211 Main Street
San Francisco, California 94105
Attn: SPNCO-R
(415) 556-2752

Sacramento
850 Capitol Mall
Sacramento, California 95814
Attn: SPKCO-O
(916) 440-2327

The Division Engineer
U.S. Engineer Division
South Pacific
630 Samson Street
San Francisco, California 94111
(415) 556-0914

EPA:

Region IX
Environmental Impact Review Officer
Environmental Protection Agency
215 Fremont Street
San Francisco, California 94105
(415) 556-2320

Colorado

State Agencies:

Lead:
Colorado Department of Health
(DEH)
Water Quality Division
4210 East 11th Avenue
Denver, Colorado 80220

(303) 331-4755
(303) 320-8333

Additional:
Dept. of Natural Res.
Division of Wildlife
6060 Broadway
Denver, Colorado 80216

(303) 297-1192

Comments:

- authority to administer the federal NPDES program
- does not administer pretreatment program
- direct question for Water Quality Division to Unit Chief of Industrial Permits and Enforcement

USFWS:
Director
Denver Federal Center
P.O. Box 25486
Denver, Colorado 80255
(303) 234-2209

EPA:
Region VIII
Environmental Impact Review Officer
Environmental Protection Agency
Lincoln Tower Building, Room 9006th
1860 Lincoln Street
Denver, Colorado 80203
(303) 837-3895

Connecticut

State Agencies:

Lead:
Department of Environmental Protection (DEP)
Water Compliance Unit
State Office Building
165 Capitol Avenue
Hartford, Connecticut 06106

Commissioner
(203) 566-2110

(203) 566-5599

Information and Education
(203) 566-3489

Additional:
None

Comments:
- ♦ full authority to administer NPDES permit program
- ♦ industrial facilities to carry out its own industrial pretreatment regulatory schemes

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

EPA:
Region I
Environmental Impact Review Officer
Environmental Protection Agency
Room 2203
John F. Kennedy Federal Building
Boston, Massachusetts 02203
(617) 223- 7210

Delaware

State Agencies:

Lead:
Department of Natural Resources and Environmental Control
Division of Water Resources
P.O. Box 1401
89 Kings Highway
Dover, Delaware 19903

Division of Water Resources
(302) 736-5731

Main Office
(302) 736-4403

Additional:
Department of Natural Resources & Environmental Control
Division of Fish and Wildlife
P.O. Box 1401
89 Kings Highway
Dover, Delaware 19903

Division of Fish and Wildlife
(302) 736-3441

Comments:
- ♦ authority to administer NPDES program for industries, but not federal facilities
- ♦ does not have authority to administer pretreatment program
- ♦ does not have authority to administer general permit program

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

EPA:
Region III
Environmental Impact Review Officer
Environmental Protection Agency
Curtis Bldg. & Walnut Streets
Philadelphia, Pennsylvania 19106
(215) 597-9814

Florida

State Agencies:

Lead:
Department of Environmental Regulation (DER)
Bureau of Permitting
2600 Blairstone Road
Tallahassee, Florida 32399-2400

(904) 488-4805

Additional:
Department of Environmental Regulation
Division of Marine Resources
2600 Blairstone Road
Tallahassee, FL 32399-2400

(904) 488-8587

Game & Fresh Water Commission
620 S. Meridian Street
Tallahassee, Florida 32301

(904) 488-1960

Comments:
- decentralize permitting process
- has not assumed control of the NPDES permitting program

USFWS:
Director
75 Spring Street, SW
Atlanta, Georgia 30303
(404) 221-3594

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer Dist.
P.O. Box 4970
Jacksonville, FL 32201
Attn: SAJOD-RP
(904) 791-2211

EPA:
Region IV
Environmental Impact Review Officer
Environmental Protection Agency
345 Courtland Street, N.E.
Atlanta, Georgia 30308
(404) 257-4727

Georgia

State Agencies:

Lead:
Water Protection Branch
Environmental Protection Division
Georgia Department of Natural Resources
205 Butler Street, SE
Suite 1058
Atlanta, Georgia 30334

Water Protection Branch
(404) 656-4708

Environmental Protection Division
(404) 656-4713

Comments:
- consolidated permitting process
- NPDES jurisdiction
- many surface waters subject to high standards

Additional:
Dept. of Natural Res.
Game & Fish Division
1362 East Tower
205 Butler St., SE
Atlanta, Georgia 30334

(404) 656-3523

FERC:
Atlanta Regional Office
730 Peachtree Street, N.E.
Room 800
Atlanta, GA 30308
(404) 881-4134

EPA:
Region IV
Environmental Impact Review Officer
Environmental Protection Agency
345 Courtland Street, N.E.
Atlanta, Georgia 30308
(404) 257-4727

USFWS:
Director
75 Spring Street, SW
Atlanta, GA 30303
(404) 221-3594

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer Dist.
P.O. Box 889
Savannah, Georgia 31402
Attn: SASOP-F
(912) 233-8822

The Division Engineer
U.S. Engineer Division
South Atlantic
510 Title Building
3 Pryor Street, S.W.
Atlanta, Georgia 30308
(404) 221-6711

Hawaii

State Agencies:

Lead:
Environmental Protection and Health Services Division (EPHSD)
Hawaii State Department of Health
P.O. Box 3378
1250 Punchbowl St.
Honolulu, Hawaii 96801

Director
(808) 548-4139

Additional:
Commission of Water Resource Management Division of Water
Department of Land & Natural Resources
1151 Punchbowl St.
Honolulu, Hawaii 96813

(808) 548-7439

Comments:
- ♦ full authority to operate NPDES for all facilities and pretreatment programs

USFWS:
Director
500 N.E. Multonomah Street
Portland, Oregon 97232
(503) 231-6118

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
Building 230
Ft. Shafter
Honolulu, Hawaii
Attn: PODCO-O
(806) 438-9258

EPA:
Region IX
Environmental Impact Review Officer
Environmental Protection Agency
215 Fremont Street
San Francisco, California 94105
(415) 556-2320

Idaho

State Agencies:

Lead:
Idaho Department of Health and Welfare
Division of the Environment
450 W. State Street
5th Floor
Boise, Idaho 83720

(208) 334-5839

Water Quality Bureau
(208) 334-5867

Additional:
Fish & Game Department
600 S. Walnut
Box 25
Boise, Idaho 83707

(208) 334-3700

Comments:
- decentralized program
- has not assumed authority to manage federal NPDES permit programs or the federal requirements for pretreatment of wastes entering public treatment plants
- stringent water quality designations

USFWS:
Director
500 N.E. Multonomah Street
Portland, Oregon 97232
(503) 231-6118

EPA:
Region X
Environmental Impact Review Officer
Environmental Protection Agency
1200 Sixth Avenue
Seattle, Washington 98101
(206) 442-1760

Illinois

State Agencies:

Lead:
Environmental Protection Agency
Division of Water Pollution Control
2200 Churchill Road
Springfield, Illinois 62706

(217) 782-3397

Additional:
Division of Water Resources
2300 S. Dirksen Parkway
Springfield, Illinois 62764

(217) 782-3862

Illinois Pollution Control Board
State of Illinois Center
100 West Randolph
Chicago, Illinois 60601

(312) 917-3620

Comments:
- NPDES jurisdiction
- approves/oversees recommendations of EPA
- permits for construction and operation of dams

FERC:
Chicago Regional Office
Federal Building, Room 3130
230 South Dearborn Street
Chicago, Illinois 60604
(312) 353-6173

USFWS:
Federal Building
Twin Cities, MN 55111
(612) 725-3500

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
219 S. Dearborn Street
Chicago, Illinois 60604
Attn: NCCCO-SP
(312) 353-6434

The District Engineer
U.S. Army Engineer District
P.O. Box Tower Building
Rock Island, Illinois 61201
Attn: NCROD-S
(309) 788-6361

The Division Engineer
U.S. Engineer Division
North Central
536 S. Clark Street
Chicago, Illinois 60605
(312) 353-6385

EPA:
Region V
Environmental Impact Review Officer
Environmental Protection Agency
230 South Dearborn Street
Chicago, Illinois 60604
(312) 353-2000

Indiana

State Agencies:

Lead:
Department of Environmental Management (DEM)
Office of Water Management
105 S. Meridian Street
P.O. Box 6015
Indianapolis, Indiana 46206-6015

Commissioner
(317) 232-8162

Office of Water Management
(317) 232-8488

Additional:
Department of Natural Resources
Division of Fish & Wildlife
608 State Office Bldg.
Indianapolis, Indiana 46204

(317) 232-4080

Comments:
- ♦ authority over NPDES permit program of all facilities
- ♦ does not have a fully approved pretreatment program

USFWS:
Director
Federal Building
Twin Cities, Minnesota 55111
(612) 725-3500

EPA:
Region V
Environmental Impact Review Officer
Environmental Protection Agency
230 South Dearborn Street
Chicago, Illinois 60604
(312) 353-2000

Iowa

State Agencies:

Lead:
Iowa Department of Natural Res.
Environmental Protection Division
Wallace State Office Building
900 E. Grand Avenue
Des Moines, Iowa 50319-0034

(515) 281-8666
(515) 281-5145

Director
(515) 281-5385

Additional:
State Conservation Commission
Division of Fish & Game
Wallace State Office Building
900 E. Grand Avenue
Des Moines, Iowa 50319-0034

(515) 281-5145

Comments:
- ♦ authority to run NPDES permit program (private and federal)
- ♦ authority to run waste pretreatment program

USFWS:
Director
Federal Building
Twin Cities, Minnesota 55111
(612) 725-3500

EPA:
Region VII
Environmental Impact Review Officer
Environmental Protection Agency
1735 Baltimore Street
Kansas City, Missouri 64108
(816) 374-5493

Kansas

State Agencies:

Lead:
Kansas Department of Health
and Environmental (DHE)
Division of Environment Water
Water Protection Bureau
Building 740
Forbes Field
Topeka, Kansas 66620-0001

(913) 296-1500

Additional:
Kansas Wildlife and Parks
Box 54A
RR 2
Pratt, Kansas 67124

(316) 672-5911

Comments:

- authority to administer all aspects of the private and federal NPDES permit program

- manages pretreatment program through a Memorandum of of Understanding with the Environmental Protection Agency

USFWS:
Director
Denver Federal Center
P.O. Box 25486
Denver, Colorado 80255
(303) 234-2209

EPA:
Region VII
Environmental Impact Review Officer
Environmental Protection Agency
1735 Baltimore Street
Kansas City, Missouri 64108
(816) 374-5493

Kentucky

State Agencies:

Lead:
Kentucky Natural Resources and
Environmental Protection Cabinet
Division of Water Quality
Capital Plaza Tower
5th Floor
Frankfort, Kentucky 40601

(502) 564-3340

Additional:
Dept. of Fish & Wildlife
Services
#1 Game Farm Rd.
Frankfort, Kentucky 40601

(502) 564-3400

Comments:

- NPDES federal approved for all facilities including general permits and pretreatment programs
- strict standards on all facilities that receive influent that is biochemically degradable or biodegradable

USFWS:
Director
75 Spring Street, SW
Atlanta, Georgia 30303
(404) 221-3594

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 59
Louisville, Kentucky 40201
Attn: ORLOP-SP
(502) 582-6461

EPA:
Region IV
Environmental Impact Review Officer
Environmental Protection Agency
345 Courtland Street, N.E.
Atlanta, Georgia 30308
(404) 257-4727

Louisiana

State Agencies:

Lead:
Office of Secretary
Department of Environmental Quality
Natural Resources Building
Office of Water Resources
625 N. Fourth Street
Baton Rouge, Louisiana 70802

(504) 342-1265

Comments:
- ♦ has not achieved delegation of NPDES and pretreatment programs

Additional:
Depart. of Wildlife & Fisheries
P.O. Box 15570
Baton Rouge, LA 70895

(504) 925-3617

USFWS:
Director
75 Spring Street, SW
Atlanta, Georgia 30303
(404) 221-3594

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 60267
New Orleans, Louisiana 70160
Attn: LMNOD-S
(504) 865-1121

EPA:
Region VI
Environmental Impact Review Officer
Environmental Protection Agency
First International Building
1201 Elm Street
Dallas, Texas 75270
(214) 767-2600

Maine

State Agencies:

Lead:
Department of Environmental Protection
Bureau of Water Quality Control
State House Station 11
Augusta, Maine 04333

Commissioner
(207) 289-2811

Additional:
Dept. of Inland Fisheries and Wildlife
284 State Street
Station #41
Augusta, Maine 04333

(207) 289-2766

Dept. of Marine Resources
State House
Station #21
Augusta, Maine 04333

(207) 289-2291

Comments:

- does not have authority to administer NPDES programs
- firms must apply for discharge permits under state regulations designed to prevent degradation of classified water to a lower class

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

EPA:
Region I
Environmental Impact Review Officer
Environmental Protection Agency
Room 2203
John F. Kennedy Federal Building
Boston, Massachusetts 02203
(617) 223-7210

Maryland

State Agencies:

Lead:
Dept. of Health & Mental Hygiene
Environmental Health Administration
Water Quality Program
Division of Technical Analysis
201 W. Preston Street
Baltimore, Maryland 21201

Department Receptionist
(301) 225-1250

Additional:
State of Maryland
Fish & Wildlife Adm.
Natural Resources Bldg.
Annapolis, Maryland 21401

(301) 267-5558

Comments:
- ♦ authority over pretreatment
- ♦ authority to administer NPDES
- ♦ waited until 6/22/87 to apply for authority to manage the program for federal facilities - waiting approval

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 1715
Baltimore, Maryland 21203
Attn: NABOP-F
(301) 962-3670

EPA:
Region III
Environmental Impact Review Officer
Environmental Protection Agency
Curtis Bldg. & Walnut Streets
Philadelphia, Pennsylvania 19106
(215) 597-9814

Massachusetts

State Agencies:

Lead:
Department of Environmental Quality Engineering
Division of Water Pollution Control
One Winter Street
Boston, Massachusetts 02108

(617) 727-5056

Water Pollution Control
(617) 292-5673

Additional:
State of Massachusetts
Dept. of Fisheries
Wildlife & Recreational Vehicles
100 Cambridge Street
Boston, MA 02202

(617) 727-3151

Comments:
- firms that need discharge permits under NPDES and pretreatment must deal with the EPA
- state has discharge regulations

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

CORP OF ENGINEERS:
The Division Engineer
U.S. Engineer Division
New England
424 Trapelo Road
Waltham, Massachusetts 02154
(617) 894-2400

EPA:
Region I
Environmental Impact Review Officer
Environmental Protection Agency
Room 2203
John F. Kennedy Federal Building
Boston, Massachusetts 02203
(617) 223-7210

Michigan

State Agencies:

Lead:
Department of Natural Resources
Surface Water Quality Division
P.O. Box 30028
Lansing, Michigan 48909

(517) 373-1949

Additional:
Dept. of Natural Res.
Fisheries Division
Box 30028
Lansing, Michigan 48909

(517) 373-1280

Comments:

- delegated authority to administer the NPDES for industrial and federal facilities and to conduct pretreatment program
- no provision for general permitting

USFWS:
Director
Federal Building
Twin Cities, Minnesota 55111
(612) 725-3500

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 1027
Detroit, Michigan 48231
Attn: NCECO-L
(313) 226-6813

EPA:
Region V
Environmental Impact Review Officer
Environmental Protection Agency
230 South Dearborn Street
Chicago, Illinois 60604
(312) 353-2000

Minnesota

State Agencies:

Lead:
Pollution Control Agency
Division of Water Quality
520 Lafayette Road
St. Paul, Minnesota 55155

(612) 297-3364

Additional:
Dept. of Natural Res.
Div. of Fish & Wildlife
Fish Section
300 Centennial Bldg.
658 Cedar Street
St. Paul, Minnesota 55155

(612) 296-6157
1-800-652-9747

Comments:
- ♦ authority to regulate NPDES and pretreatment programs

USFWS:
Director
Federal Building
Twin Cities, Minnesota 55111
(612) 725-3500

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
1135 USPO & Custom House
St. Paul, Minnesota 55101
Attn: NCSCO-S
(612) 725-5819

EPA:
Region V
Environmental Impact Review Officer
Environmental Protection Agency
230 South Dearborn Street
Chicago, Illinois 60604
(312) 353-2000

Mississippi

State Agencies:

Lead:
Mississippi Dept. of Natural Res.
Southport Center
2380 Highway 80 W.
P.O. Box 20305
Jackson, Mississippi 39209

Director
(601) 961-5000

Pollution Control Bureau
(601) 961-5100

Comments:
- approved to administer the NPDES and pretreatment program

Additional:
Dept. of Wildlife Conservation
Bureau of Fisheries and Wildlife
Southport Mall
P.O. Box 451
Jackson, MS 39205
(601) 961-5300

USFWS:
Director
75 Spring Street, SW
Atlanta, Georgia 30303
(404) 221-3594

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 60
Vicksburg, Mississippi 39180
Attn: LMKOD-F
(801) 636-1311

The Division Engineer
U.S. Engineer Division
Lower Mississippi Valley
P.O. Box 80
Vicksburg, Mississippi 39180
(601) 634-5000

EPA:
Environmental Impact Review Officer
Environmental Protection Agency
345 Courtland Street, N.E.
Atlanta, Georgia 30308
(404) 257-4727

Missouri

State Agencies:

Lead:
Department of Natural Resources
Division of Environmental Quality
Jefferson State Office Building
Jefferson City, Missouri 65102

Main Office
(314) 751-3332

Water Quality Program
(314) 751-1300

Additional:
Dept. of Conservation
Fisheries Division
P.O. Box 630
Jefferson City, MO 65101

(314) 751-4211

Comments:

- authority to manage NPDES program for all federal facilities
- may issue general permits
- manages federal pretreatment program

USFWS:
Director
Federal Building
Twin Cities, Minnesota 55111
(612) 725-3500

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
700 Federal Building
601 E. 12th Street
Kansas City, Missouri 64106
Attn: MRKOD-D
(816) 374-3645

The District Engineer
U.S. Army Engineer District
210 No. 12th Street
St. Louis, Missouri 63101
Attn: LMSOD-NP
(314) 268-2872

EPA:
Region VII
Environmental Impact Review Officer
Environmental Protection Agency
1735 Baltimore Street
Kansas City, Missouri 64108
(816) 374-5493

Montana

State Agencies:

Lead:
Department of Health & Environmental Sciences
Environmental Sciences Division
Coswell Building
Helena, Montana 59601

(406) 444-2406

Additional:
Dept. of Fish, Wildlife & Parks
1420 East Sixth
Helena, Montana 59620

(406) 444-2449

Environmental Quality Control
State Capitol
Helena, Montana 59620

(406) 444-3742

Comments:
- full authority to administer NPDES permit program
- pretreatment programs have not received federal authority

USFWS:
Director
Denver Federal Center
P.O. Box 25486
Denver, Colorado 80255
(303) 234-2209

EPA:
Region VIII
Environmental Impact Review Officer
Environmental Protection Agency
Lincoln Tower Building, Room 9006th
1860 Lincoln Street
Denver, Colorado 80203
(303) 837-3895

Nebraska

State Agencies:

Lead:
Dept. of Environmental Control
State Office Building
301 Centennial Mall South
4th Floor, P.O. Box 94877
Lincoln, Nebraska 68509

Director
(402) 471-2186

Chief, Water Quality Division
(402) 471-4432

Comments:
- ♦ full authority to administer NPDES permit program and requirements for pretreatment of industrial discharge into sewer systems

Additional:
Game & Parks Commission
Fisheries Division
2200 N. 33rd Street
P.O. Box 30370
Lincoln, Nebraska 68503

(402) 464-0641

USFWS:
Director
Denver Federal Center
P.O. Box 25486
Denver, Colorado 80255
(303) 234-2209

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
8014 USPO & Courthouse
215 N. 17 Street
Omaha, Nebraska 68102
Attn: MROOP-N
(402) 221-4133

The Division Engineer
U.S. Engineer Division
Missouri River
P.O. Box 103
Downtown Station
Omaha, Nebraska 68101
(402) 221-7200

EPA:
Region VII
Environmental Impact Review Officer
Environmental Protection Agency
1735 Baltimore Street
Kansas City, Missouri 64108
(816) 374-5493

Nevada

State Agencies:

Lead:
Division of Environmental Protection
Department of Conservation & Natural Resources
201 South Falls Street
Carson City, Nevada 89710

(702) 885-4360
(702) 885-4670

Water Resources Division
(702) 885-4380

Additional:
Department of Wildlife
Fisheries Division
Box 10678
Reno, Nevada 89520

(702) 789-0500

USFWS:
Director
500 N.E. Multonomah Street
Portland, Oregon 97232
(503) 231-6118

EPA:
Region IX
Environmental Impact Review Officer
Environmental Protection Agency
215 Fremont Street
San Francisco, California 94105
(415) 556-2320

New Hampshire

State Agencies:

Lead:
The Department of Environmental Services
Water Supply and Pollution Control Commission
Hazen Dr., Box 95
Concord, New Hampshire 03301

(603) 871-3503

Additional:
Fish & Game Department
34 Bridge Street
Concord, NH 03301

(603) 271-3421

Comments:
- 8 small regional offices only Portsmouth issues permits
- has not assumed management authority over the NPDES permit program or the federal pretreatment requirements

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

EPA:
Region I
Environmental Impact Review Officer
Environmental Protection Agency
Room 2203
John F. Kennedy Federal Building
Boston, Massachusetts 02203
(617) 223-7210

New Jersey

State Agencies:

Lead:
Office of the Commissioner
Dept. of Environmental Protection
401 East State Street
P.O. Box CN 029
Trenton, New Jersey 08625

Main Office
(609) 292-2885

Additional:
Division of Fish, Game & Wildlife
CN 400
Trenton, New Jersey 08625

(609) 292-2965

Division of Water Res.
CN 029
Trenton, New Jersey 08625

(609) 292-1637

Comments:
- full authority to administer NPDES permit program and requirements for pretreatment of industrial discharge into sewer systems

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

EPA:
Region II
Environmental Impact Review Officer
Environmental Protection Agency
Room 1009
26 Federal Plaza
New York, New York 10007

New Mexico

State Agencies:

Lead:
Environmental Improvement Division
New Mexico Department of Health
Environment
P.O. Box 968
Santa Fe, New Mexico 87504-0968

Surface Water Quality Bureau
(505) 827-2804

Additional:
Game and Fish Dept.
Villagra Bldg.
Santa Fe, NM 87503

(505) 827-7899

Comments:
- ♦ has not assumed full authority to manage any of the federal water quality control programs

USFWS:
Director
500 Gold Avenue SW
Albuquerque, New Mexico 87103
(505) 474-2321

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 1580
Albuquerque, New Mexico 87103
Attn: SWACO-OR
(505) 766-2776

EPA:
Region VI
Environmental Impact Review Officer
Environmental Protection Agency
First International Building
1201 Elm Street
Dallas, Texas 75270
(214) 767-2600

State Agencies:

Lead:
New York Department of
Environmental Conservation
Division of Regulatory Affairs
50 Wolf Road
Albany, New York 12233-3500

(518) 474-6674

Dept. of Environmental Conservation
Division of Fish & Wildlife
50 Wolf Road
Albany, New York 12233-3500

(518) 457-5691

Division of Water
50 Wolf Road
Albany, New York 12233-3500

(518) 457-3495

Comments:
- decentralized to every extent possible
- regional offices carry out the permitting process
- responsibility to administer the federal NPDES for all facilities
- may not issue general permits
- does not have authority to manage the federal pretreatment program in all areas

FERC:
New York Regional Office
26 Federal Plaza, Room 2207
New York, New York 10278
(212) 264-3687

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
1776 Niagara Street
Buffalo, New York 14207
Attn: BCBCO-S
(716) 876-5454

The District Engineer
U.S. Army Engineer District
26 Federal Plaza
New York, New York 10007
Attn: NANOP-E
(212) 264-3996

The Division Engineer
U.S. Engineer Division
North Atlantic
90 Church Street
New York, New York 10007
(212) 264-7464

USFWS:
Director
1 Gateway Cntr, Suite 700
Newton Corner, MA 02158
(617) 829-9200

EPA:
Region II
Environmental Impact
Review Officer
EPA
Room 1009, 26 Federal
Plaza
New York, New York 10007
(212) 264-2525

North Carolina

State Agencies:

Lead:
North Carolina Department of
Natural Resources and Community
Development
Division of Environmental Management
Archdale Building
512 N. Salisbury Street
Raleigh, North Carolina 27611-7689

OR

P.O. Box 27687
Raleigh, North Carolina 27611-7687

(919) 733-4984

Water Quality Division
(919) 733-5083

Comments:
- ♦ full authority to administer the federal NPDES permit program
- ♦ authority to administer pretreatment requirement for firms discharging wastes into publicly owned treatment works

Additional:
Dept. of Natural Res.
& Community Development
Division of Marine
Fisheries
P.O. Box 769
Morehead City, NC 27611
(919) 726-7021

N. C. Wildlife Resource
Commission
Archdale Building
512 N. Salisbury St.
Raleigh, NC 27611
(919) 733-3633

USFWS:
Director
75 Spring Street, SW
Atlanta, Georgia 30303
(404) 221-3594

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 1890
Wilmington, North Carolina 28401
Attn: SAWCO-E
(919) 763-9971

EPA:
Region IV
Environmental Impact Review Officer
Environmental Protection Agency
345 Courtland Street, N.E.
Atlanta, Georgia 30308
(404) 257-4727

North Dakota

State Agencies:

Lead:
State Department of Health
Division of Water Supply and
Pollution Control
Box 5520
Bismarck, North Dakota 58502

Division Water Supply and
Pollution Control
(701) 224-2354

Additional:
State Game & Fish Dept.
100 N. Bismarck Express.
Bismarck, ND 58501

(701) 221-6300

Comments:

- authority to manage federal NPDES program for all source except federal facilities
- does not have final authority over federal pretreatment program
- has water quality standards for dissolved oxygen and other parameters
- only 3 cities - Bismarck, Fargo and Grand Falls are large enough to fall under this program requirements

USFWS:
Director
Denver Federal Center
P.O. Box 25486
Denver, Colorado 80255
(303) 234-2209

EPA:
Region VIII
Environmental Impact Review Officer
Environmental Protection Agency
Lincoln Tower Building, Room 9006th
1860 Lincoln Street
Denver, Colorado 80203
(303) 837-3895

Ohio

State Agencies:

Lead:
Ohio Environmental Protection Agency
P.O. Box 1049
1800 Water Mark Dr.
Columbus, OH 43266-0149

Director's Office
(614) 481-7050

Public Interest Center
(714) 481-2160

Additional:
State of Ohio
Dept. of Natural Res.
Division of Wildlife
Fountain Square
Columbus, Ohio 43224

(614) 466-7313

Comments:
- ♦ full authority over NPDES for all source categories
- ♦ pretreatment program as it applies to firms that would discharge into publicly owned treatment works

USFWS:
Director
Federal Building
Twin Cities, Minnesota 55111
(612) 725-3500

CORP OF ENGINEERS:
The Division Engineer
U.S. Engineer Division
Ohio River
P.O. Box 1159
Cincinnati, Ohio 45201

EPA:
Region V
Environmental Impact Review Officer
Environmental Protection Agency
230 South Dearborn Street
Chicago, IL 60604
(312) 353-2000

Oklahoma

State Agencies:

Lead:
Oklahoma Water Resources Board
Industrial Wastewater Discharges
P.O. Box 53585
1000 N.E. 10th Street
Oklahoma City, Oklahoma 73152

Water Quality Division
Chief (405) 271-2541

Comments:
- water programs managed by more than one department
- not assumed authorization over NPDES or federally prescribed industrial discharge pretreatment

Additional:
State Dept. of Health
Municipal and Domestic Wastewater Discharges
P.O. Box 53551
1000 N.E. 10th Street
Oklahoma City, OK 73152

Permits & Compliance Div.
Director (405) 271-7327

State Dept. of Wildlife Conservation
Environmental Section
1801 N. Lincoln
P.O. Box 53466
Oklahoma City, OK 73152
(405) 521-4601

USFWS:
Director
500 Gold Avenue SW.
Albuquerque, New Mexico 87103
(505) 474-2321

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 61
Tulsa, Oklahoma 74102
Attn: SWTOD-N
(918) 581-7351

EPA:
Region VI
Environmental Impact Review Officer
Environmental Protection Agency
First International Building
1201 Elm Street
Dallas, Texas 75270
(214) 767-2600

Oregon

State Agencies:

Lead:
Oregon Dept. of Environmental Quality
Water Quality Division
811 S.W. Sixth Avenue
Portland, Oregon 97204

(503) 229-5607

Director
(503) 229-5395

Water Quality Division
(503) 229-5356

Additional:
Dept. of Fish & Wildlife

(503) 229-5551

Comments:

- decentralized permitting process
- authority to manage federal NPDES, even federal facilities, to write general permits for broad discharge categories, and to operate its own effluent pretreatment program
- besides discharge permits, other permits may be necessary

FERC:
Portland Regional Office
1120 South West 5th Street
Suite 1340
Portland, Oregon 97204
(503) 294-5840

USFWS:
Director
500 N.E. Multonomah Street
Portland, Oregon 97232
(503) 231-6118

CORP OF ENGINEERS:
The District Engineer
U.S. Army Eng. District
P.O. Box 2946
Portland, Oregon 97206
Attn: NPPND-RF
(503) 221-6997 OR 6021

EPA:
Region X
Environmental Impact Review Offcr.
Environmental Protection Agency
1200 Sixth Avenue
Seattle, Washington 98101
(206) 442-1760

The Division Engineer
U.S. Engineer Division
North Pacific
P.O. Box 2870
Portland, Oregon 97208
(503) 221-3700

Pennsylvania

State Agencies:

Lead:
Department of Environmental Res.
Bureau of Water Quality
200 N. 3rd Street
P.O. Box 2063
Fulton Building
Harrisburg, Pennsylvania 17120

(717) 787-2814

Director for Policy Planning
(717) 773-8727
(717) 787-2666

Additional:
Fish Commission
P.O. Box 1673
Harrisburg, PA 17105

(717) 657-4518

Comments:

- decentralized to the maximum extent possible
- full authority to administer federal NPDES permit program all facilities including federal facilities
- established necessary framework to issue general permits, but has not received federal authority
- pretreatment program still managed in cooperation with the U.S. EPA

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, MA 02158
(617) 829-9200

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer Dist.
US Custom House
2nd & Chestnut Streets
Philadelphia, PA 19106
Attn: NAPOP-R
(215) 597-2812

EPA:
Region III
Environmental Impact Review Offcr.
Environmental Protection Agency
Curtis Bldg. & Walnut Streets
Philadelphia, PA 19106
(215) 597-9814

The District Engineer
U.S. Army Engineer Dist.
1884 Federal Building
1000 Liberty Avenue
Pittsburgh, PA 15222
Attn: ORPOP-S
(412) 644-6872

Rhode Island

State Agencies:

Lead:
Rhode Island Dept. of Env. Management
Division of Water Resources
291 Promenade St.
Providence, RI 02908-5767

(401) 277-3961

Additional:
Dept. of Environmental Management
Division of Fish & Wildlife
83 Park St.
Providence, RI 02903

(401) 789-3094

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

EPA:
Region I
Environmental Impact Review Officer
Environmental Protection Agency
Room 2203
John F. Kennedy Federal Building
Boston, Massachusetts 02203
(617) 223-7210

South Carolina

State Agencies:

Lead:

Deputy Commissioner for
Environmental Control
Department of Health and
Environmental Control
Bureau of Waste Water
and Stream Quality Control
J. Marion Sims Building
2600 Bull St.
P.O. Box 11628
Columbia, South Carolina 29201

(803) 734-4880

Water Pollution Control Bureau
(803) 734-4880

Additional:

Wildlife & Marine Resources
Department
Division of Game & Fresh
Water Fisheries
Rembert C. Dennis Bldg.
P.O. Box 167
Columbia, SC 29202

(803) 353-8232

Wildlife & Marine Resources
Department
Division of Marine Resources
Rembert C. Dennis Bldg.
P.O. Box 167
Columbia, SC 29202

(803) 734-3992
(803) 795-6350

Comments:

- jurisdiction over the federal NPDES permit program for both industrial and federal facilities
- has full approved pretreatment program
- State requires permit to discharge

USFWS:

Director
75 Spring Street, SW
Atlanta, Georgia 30303
(404) 221-3594

CORP OF ENGINEERS:

The District Engineer
U.S. Army Engineer District
P.O. Box 919
Charleston, SC 29402
Attn: SACCO-P
(803) 577-4171

EPA:

Region IV
Environmental Impact Review Officer
Environmental Protection Agency
345 Courtland Street, N.E.
Atlanta, Georgia 30308
(404) 257-4727

South Dakota

State Agencies:

Lead:
Department of Water and
Natural Resources (DWNR)
Department of Water Quality
Joe Foss Building, Rm. 413
Pierre, South Dakota 57501

(605) 773-3151

Additional:
Game Fish & Parks Dept.
Fisheries Division
445 East Capitol
Pierre, SD 57501-3185

(605) 773-3384

Comments:
- ♦ has not assumed full delegation of any of the federal water quality protection programs

USFWS:
Director
Denver Federal Center
P.O. Box 25486
Denver, Colorado 80255
(303) 234-2209

EPA:
Region VIII
Environmental Impact Review Officer
Environmental Protection Agency
Lincoln Tower Building, Room 9006th
1860 Lincoln Street
Denver, Colorado 80203
(303) 837-3895

Tennessee

State Agencies:

Lead:
Department of Health and Environment
Division of Water Pollution Control
Industrial Facilities Section
TERRA Building
150 Ninth Avenue, N.
Nashville, Tennessee 37219-5405

Division of Water Pollution Control
(615) 741-7883

Comments:
- ♦ authority federal NPDES for industry and federal facilities
- ♦ authority for state pretreatment program

Additional:
Wildlife Resource Agency
Fish Management Division
P.O. Box 40747
Ellington Agricultural Center
Nashville, TN 37204
(615) 360-0500

USFWS:
Director
75 Spring Street, SW
Atlanta, Georgia 30303
(404) 221-3594

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
868 Federal Office Building
Memphis, Tennessee 38103
Attn: LMMOD-NN
(901) 521-3471

The District Engineer
U.S. Army Engineer District
P.O. Box 1070
Nashville, Tennessee 37202
Attn: ORNOP-F
(615) 251-5181

EPA:
Region IV
Environmental Impact Review Officer
Environmental Protection Agency
345 Courtland Street, N.E.
Atlanta, Georgia 30308
(404) 257-4727

State Agencies:

Lead:
Texas Water Commission
P.O. Box 13087
Capitol Station
Austin, Texas 78711

(512) 463-8875

Additional:
Parks & Wildlife Dept.
Fisheries Division
4200 Smith School Rd.
Austin, Texas 78744

(512) 479-4800

Comments:
- firms subject to the federal NPDES or pretreatment must deal with the EPA as well as the TWC

USFWS:
Director
500 Gold Avenue SW.
Albuquerque, New Mexico 87103
(505) 474-2321

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 17300
Ft. Worth, Texas 76102
Attn: SWFOD-P
(817) 334-2814

The District Engineer
U.S. Army Engineer District
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Galveston, Texas 77553
Attn: SWGCO-OC
(713) 763-1211

The Division Engineer
U.S. Engineer Division
Southwestern
1114 Commerce Street
Dallas, Texas 75242
(214) 767-2502

EPA:
Region VI
Environmental Impact Review Officer
Environmental Protection Agency
First International Building
1201 Elm Street
Dallas, Texas 75270
(214) 767-2600

Utah

State Agencies:

Lead:
Division of Environmental Health
Bureau of Water Pollution Control
Utah Department of Health
288 North 1460 West
Salt Lake City, Utah 84116

(801) 538-6146

Additional:
State Dept. of Natural Resources
Division of Wildlife Res.
Fisheries Management
1596 W. North Temple

(801) 533-9333

Comments:

- more than 50% of Utah's land is federally controlled
- many Indian Reservations where tribal council decisions hold sway
- does not have authority to administer federal water discharge or pretreatment programs
- Utah has their own standards use designations and discharge prohibitions

USFWS:
Director
Denver Federal Center
P.O. Box 25486
Denver, Colorado 80255
(303) 234-2209

EPA:
Region VIII
Environmental Impact Review Officer
Environmental Protection Agency
lincoln Tower Building, Room 9006th
1860 Lincoln Street
Denver, Colorado 80203
(303) 837-3895

Vermont

State Agencies:

Lead:
Agency of Environmental Conservation
Department of Water Resources
and Environmental Engineering
State Office Building
Montpelier, Vermont 05602

Director - Water Quality
(802) 828-3361
(802) 828-2871

Comments:
- ♦ authority NPDES program
- ♦ approved pretreatment program

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

EPA:
Region I
Environmental Impact Review Officer
Environmental Protection Agency
Room 2203
John F. Kennedy Federal Building
Boston, Massachusetts 02203
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Virginia

State Agencies:

Lead:
State Water Control Board
Permits Program
Office of Water Resources
P.O. Box 11143
Richmond, Virginia 23230

(804) 367-1868

Additional:
Commission of Game & Inland Fisheries
4010 W. Broad Street
Box 11104
Richmond, VA 23230

(804) 257-1000

Comments:

- approval of pretreatment program is pending
- SWCB administers UPDES and UPA permits program
- SWCB issues Virginia Water protection (VWP) permits (as Section 401 Certification) to protect instream beneficial uses (effective 7/1/89)

USFWS:
Director
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Newton Corner, Massachusetts 02158
(617) 829-9200

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
803 Front Street
Norfolk, Virginia 23510
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(804) 446-3652

EPA:
Region III
Environmental Impact Review Officer
Environmental Protection Agency
Curtis Bldg. & Walnut Streets
Philadelphia, PA 19106
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Washington

State Agencies:

Lead:
Washington Department of Ecology
Mail Stop, PV-11
St. Martin's College
Campus-Lacey
Olympia, Washington 98504-8711

(206) 459-6022

Additional:
Dept. of Fisheries
115 General Admin. Bldg.
Olympia, WA 98504

(206) 753-6600

Comments:

- ♦ authority to administer NPDES as well as its own industrial effluent pretreatment scheme
- ♦ pretreatment authority - using it to reduce amount of total pollutants entering state water through privately owned treatment works

USFWS:
Director
500 N.E. Multonomah Street
Portland, Oregon 97232
(503) 231-6118

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
P.O. Box 3-3755
Seattle, Washington 98134
Attn: NPSOP-RF
(206) 764-3495

The District Engineer
U.S. Army Engineer District
Building 602
City-County Airport
Walla Walla, Washington 99362
Attn: NPWOP-NF
(509) 525-5500

EPA:
Region X
Environmental Impact Review Officer
Environmental Protection Agency
1200 Sixth Avenue
Seattle, Washington 98101
(206) 442-1760

West Virginia

State Agencies:

Lead:
West Virginia Department
of Natural Resources
Office of Environmental
and Regulatory Affairs
1900 Kanawha Blvd., East
Charleston, WV 25305

(304) 348-2761

Additional:
WVDNR - Water Resources
Division
1200 Greenbrier Street
Charleston, WV 25305

(304) 348-2107

WVDNR - Wildlife Res.
1900 Kanawha Blvd.
East Charleston, WV 25305

(304) 348-2771

Comments:

- general permitting approved
- approved pretreatment and NPDES authority
- State 401 Certification
- Fishery concerns related to water quality

USFWS:
Director
1 Gateway Center, Suite 700
Newton Corner, Massachusetts 02158
(617) 829-9200

CORP OF ENGINEERS:
The District Engineer
U.S. Army Engineer District
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Huntington, West Virginia 25721
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(304) 529-2318

EPA:
Region III
Environmental Impact Review Officer
Environmental Protection Agency
Curtis Bldg. & Walnut Streets
Philadelphia, Pennsylvania 19106
(215) 597-9814

Wisconsin

State Agencies:

Lead:
Wisconsin Department of Natural Resources
Bureau of Water Resources Management
101 S. Webster Street
Box 7921
Madison, Wisconsin 53707

(608) 267-7610

Additional:
Dept. of Natural Res.
Bureau of Fish Management
Box 7921
Madison, Wisconsin 53707

Bureau of Environmental Analysis & Review
101 S. Webster Street
Box 7921
Madison, Wisconsin 53707

(608) 266-0245

Comments:

- authority to meet water quality standards for all parameters
- authority NPDES for all facilities
- pretreatment of industrial wastes before it enters publicly owned treatment works is fully approved
- general permit scheme approved

USFWS:
Director
Federal Building
Twin Cities, Minnesota 55111
(612) 725-3500

EPA:
Region V
Environmental Impact Review Officer
Environmental Protection Agency
230 South Dearborn Street
Chicago, Illinois 60604
(312) 353-2000

Wyoming

State Agencies:

Lead:
Department of Environmental Quality
Water Quality Division
Herschler Bldg, 4 West
Cheyenne, Wyoming 82002

Water Quality Division
(307) 777-7391

Additional:
Game & Fish Department
Cheyenne, Wyoming 82002

(307) 777-7631

Comments:

- jurisdiction over the NPDES private and federal
- has not assumed authority over all aspects of federal pretreatment program
- no discharge before permit is issued

USFWS:
Director
Denver Federal Center
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Denver, Colorado 80255
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Appendix B

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Appendix C

ADDITIONAL RESERVOIR / DO BACKGROUND MATERIAL

The following sections are provided to enhance the material presented in Section 1, Description of the Problem. The sections compare the environmental mechanisms of lakes and reservoirs, review the literature pertinent to dissolved oxygen in reservoirs, and provide specific case studies of the natural recovery of DO in tailwaters.

C.1 COMPARISON OF LIMNOLOGICAL FACTORS BETWEEN LAKES AND RESERVOIRS

Limnological factors that affect low DO in reservoirs and their releases include thermal stratification, retention time, inflow water quality, reservoir DO consumption processes, reservoir morphology, and hydrologic cycle. These same factors affect DO in lakes. It is helpful to review the similarities and differences between lakes and reservoirs because many investigators tend to relate DO dynamics in reservoirs to information published on lakes.

Thornton, (Ref. C-1) stated that one of the major differences between reservoirs and lakes in the United States is their latitudinal distribution. The majority of lakes occur in the glaciated portion of the United States with a smaller number of lakes occurring in Florida. The glaciated areas are primarily located around latitude 45°N. The majority of reservoirs are located throughout the southeastern, central, southwestern, and western United States. A smaller number are located around 45°N latitude representing the small number of reservoir projects on the Missouri and Columbia river systems and some smaller New England projects. This distribution of reservoir projects and lakes results in these systems being exposed to significantly different climatology. This observation is significant because most limnological knowledge and experience is based primarily on the study of lakes located around 45°N. It is generally assumed that fundamental limnological processes such as primary production,

respiration, decomposition, etc. are similar in lakes and reservoirs; however, climatology significantly affects the occurrence and rates of reaction of all these processes.

Thornton also compared the morphometric characteristics of lakes and reservoirs and reported that reservoirs have greater drainage and surface areas, drainage area/surface area ratios, mean and maximum depths, shoreline development ratios, and areal waterloads than lakes. The greater DA/SA ratio is a measure of a likelihood for greater hydrologic and water quality contaminant loading to reservoirs. One observation made by Thornton was that thunderstorms are more frequent in the southern latitudes where reservoirs are located and that because contaminants from terrestrial sources are transported significantly more during storm events. Reservoirs typically occur in areas with higher suspended solids concentrations. Thornton reported that storm events generally contribute at least an order of magnitude more phosphorus than occurs during comparable base flow periods. He reported that one major storm event to DeGray Lake, Arkansas, contributed a phosphorus load comparable to the entire annual phosphorus load during baseflow. Shoreline development can lead to higher biological productivity in reservoirs if extensive littoral areas develop, potentially resulting in more DO consumption in such reservoirs.

Kimmel and Groeger (Ref. C-2) reported that reservoirs occupy an intermediate position between rivers and natural lakes on a continuum of aquatic ecosystems (Figure C-1). They reported that considerable overlap occurs and many similarities exist between natural lakes and reservoirs; however, some obvious differences separate the typical lake from reservoirs, i.e., basin morphology, hydrodynamics and hydraulic retention times, extent of water level fluctuations, and surface versus subsurface outflows. They also reported that, as a group, reservoirs appear to be somewhat more productive than natural lakes in terms of phytoplankton productivity. Although reservoir productivity falls within the same range as those for lakes, oligotrophic reservoirs are much rarer than oligotrophic lakes and the relative percentage of eutrophic impoundments is considerably higher than eutrophic lakes. They attributed this observation to the fact that most reservoirs have significantly higher ratios of watershed

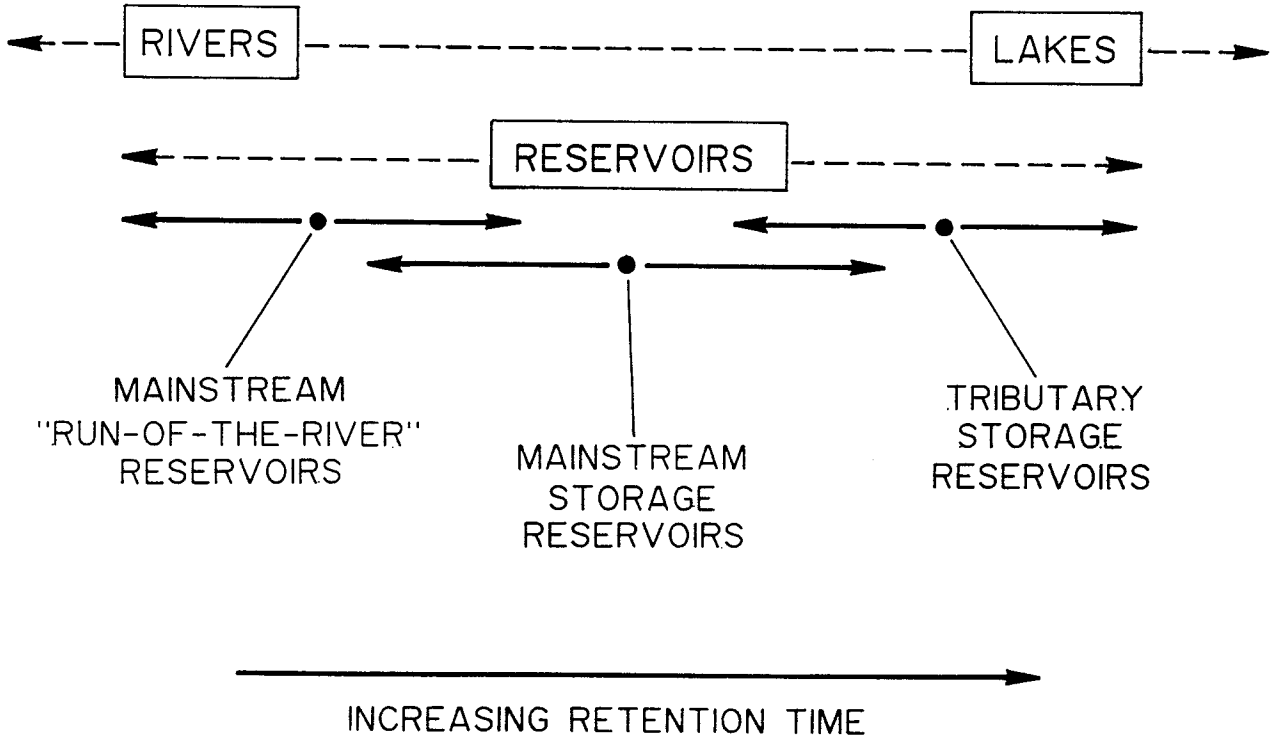


Figure C-1. Reservoirs occupy an intermediate position between rivers and natural lakes on a continuum of aquatic ecosystems. The extent of riverine influence and the hydraulic retention time determine the relative positions of various impoundment types (e.g., mainstream run-of-the-river, mainstream storage, tributary storage) along the river-lake continuum (Ref. C-2).

drainage area to lake surface areas and receive higher sediment and nutrient loads than do most natural lakes. They also hypothesized that more reservoirs than natural lakes are located in fertile drainage areas.

Kimmel and Groeger also reported that because of longitudinal gradients in water quality and productivity within reservoirs that lake trophic classifications are less appropriate for impoundments. Within a reservoir the fertility of the water generally decreases down-lake as the effective nutrient supply decreases. Trophic state has been reported to shift from more eutrophic to more oligotrophic conditions along the riverine-transitional-lacustrine zone gradient (Figure C-2).

Walker (Ref. C-3) reported that the simple phosphorus-to-chlorophyll relationships applied to eutrophication analysis for lakes are not as successful for reservoirs because of the significant effects of other factors on algal production, including nitrogen, turbidity, depth, and flushing rate. He reported that both Corps and non-Corps reservoirs tend to differ from natural lakes mainly with respect to optical parameters and residence time, suggesting that light limitation and flushing rate are potentially more important as controlling factors for algal growth in reservoirs, on the average. He also concluded that the apparent differences between lakes and reservoirs with respect to the chlorophyll-to-phosphorus ratio is explained by watershed characteristics which affect the amount and partitioning of nutrients entering reservoirs and the generation and transport of sediment into reservoirs.

Groeger and Kimmel (Ref. C-4) reported on another very significant factor that affects DO in reservoirs and lakes. Decomposition of organic matter is the most significant factor that affects DO consumption within reservoirs. The major source of organic matter is usually the inflow to reservoirs, which is allochthonous input, but another source is internal production of organic matter primarily through the growth of algae and aquatic weeds, which is autochthonous organic matter. Reservoirs usually receive large allochthonous organic matter loads relative to most natural lakes where autochthonous production is more commonly predominant. Allochthonous organic

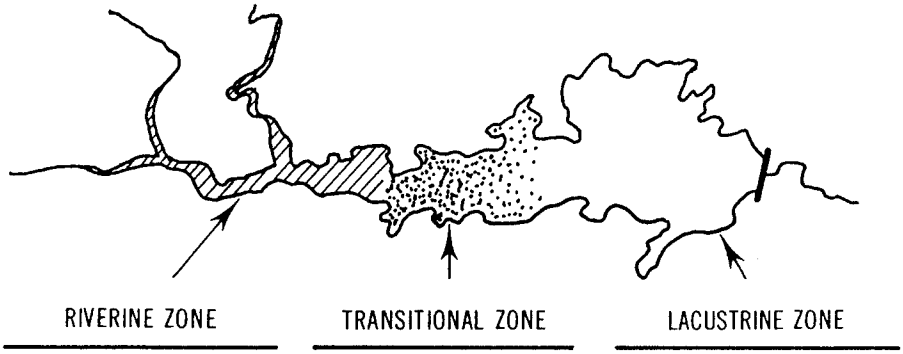


Figure C-2. Longitudinal zonation for factors controlling primary productivity, phytoplankton biomass, and trophic state within reservoir basins (Ref. C-2). See Table 3-1 for a definition of how these biological factors differ between the zones.

matter enters reservoirs primarily during heavy watershed runoff events and settles to the bottom of the reservoir at the earliest opportunity when velocities are low enough to allow settling and to reduce erosion and scour. Groeger and Kimmel referenced one study where 40 percent of the annual allochthonous organic matter input to a mainstream Michigan reservoir entered and flowed through the system during a four-week period of high spring flow. They also referenced other findings where autochthonous organic matter is generally believed to have higher energy and nutrient content per unit weight and to be more biologically labile than allochthonous material. They presented a tabular summary of all current literature on the ratio of autochthonous to allochthonous inputs for lakes and reservoirs. Organic carbon, particularly particulate matter and sediment content, has rarely been measured in reservoirs except for research studies, yet it is the most significant water constituent that affects DO and nutrient cycling in reservoirs.

Attempts in the past have been made to relate the level of eutrophication or algal concentrations to hypolimnetic DO; however, such attempts have been unsuccessful, especially for reservoirs. One main reason for this lack of success is the inability to use simple phosphorus/chlorophyll models for reservoirs since other factors such as turbidity can control algal productivity. Hence, the linkage between nutrient level and DO depletion can be no stronger than the linkage between nutrients and algal productivity. Another major consideration is the fact that hypolimnetic oxygen levels are usually affected by sediment oxygen demand which is a function of allochthonous organic material in addition to autochthonous organic material; hence, the relationship between nutrients and DO level should not necessarily be expected to be a strong one. The report on Eutrophication of Waters by the Organization for Economic/Cooperation and Development (Ref. C-5) reported the lack of success in relating phosphorus-loading measurements with oxygen depletion, especially for reservoirs.

Wetzel (Ref. C-6) summarized comparative characteristics and properties between reservoirs and lakes, and his summary table is reprinted in Table C-1.

Table C-1

COMPARATIVE CHARACTERISTICS AND PROPERTIES BETWEEN RESERVOIR AND NATURAL LAKE ECOSYSTEMS

Properties	Reservoirs	Natural Lakes
Geographical distribution	Predominantly southern (N. Hemisphere) in non-glaciated regions	Predominantly northern in glaciated regions
Climate	Precipitation often low and evaporation high or greater than precipitation	Precipitation commonly exceeds evaporative losses
Drainage basins	Usually narrow, elongated lake basin in base of drainage basin; area large in comparison to lake area (ca. 100:1 to 300:1)	Circular, lake basin usually central, area usually small in comparison to lake area (ca: 10:1).
Shoreline development	Great; astatic	Relatively low; stable
Water level fluctuations	Large, irregular	Small, stable
Thermal stratification	Variable, irregular, often too shallow to stratify in riverline and transitional zones; often can temporarily stratify in lacustrine zones	Natural regime; often dimietic or monomictic
Inflow	Most runoff to lake via river tributaries (high stream orders); penetration into stratified strata complex (over-, inter-, underflows) and often flow is directed along old riverbend valley	Run off to lake via small tributaries (low stream orders) and diffuse sources; penetration into stratified waters small and dispersive
Outflow (withdrawal)	Highly irregular with water use; withdrawal from surface layers or from hypolimnion	Relatively stable; surface water
Flushing rates	Short, variable (days to several weeks); Increase with surface withdrawal, disruption of stratification with hypolimnetic withdrawal	Long, relatively constant (1 to many years)
Sediment loading	High with large drainage basin area; flood plains large; deltas large, channelized; gradation rapid	Low to very low; deltas small, broad; gradation slow

Table C-1 (continued)

Properties	Reservoirs	Natural Lakes
Suspended sediment in water	High, variable; high percentage clay and silt particles; turbidity high	Low to very low; turbidity low
Allochthonous particulate organic matter (POM)	Moderate, especially fine POM during spates and inundation of floodplains	Low to very low
Water temperatures	Somewhat higher (generally more southern climate)	Generally lower (concentrated in more northern climatic regions)
Dissolved oxygen	Somewhat lower solubilities (higher temperatures); great horizontal variability with inflow, withdrawal, and POM loading patterns; metallimnetic oxygen minima more common than maxima	Somewhat higher solubilities (lower temperatures); small horizontal variability metalimnetic oxygen maxima more common than minima
Light extinction	Horizontal gradients (in kilometers) predominate; light extinction irregular and often very high, particularly in riverine and transitional zones from from abiogenic particulate matter; euphotic zone commonly increases in lacustrine zones	Vertical light gradients (in meters) predominate; variable but relatively low extinction from dissolved organic compounds and biogenic particulate matter
External nutrient loadings	Generally higher than to natural lakes (larger drainage basin, more human activity, greater water level fluctuations); variable, often unpredictable	Variable but relatively predictable; loadings often moderated by biogeochemical influences of wetland/littoral interface zones
Nutrient dynamics	Horizontal gradients predominate; dependent upon sedimentation rates, residence times, and flow regimes; concentrations in water decrease with distance from headwaters, irregular internal loading	Vertical gradients dominate; often low internal loading, particularly in lakes without severe culturally induced eutrophication

Table C-1 (continued)

Properties	Reservoirs	Natural Lakes
Dissolved organic matter (DOM)	Allochthonous and benthic sources predominate; irregular, often high; refractory DOM predominates	Allochthonous and littoral/ wetland sources predominate; relatively constant, often high; refractory DOM predominates
Littoral zone/wetland	Irregular and limited by severe water level fluctuations	Dominates primary production in most lakes; important to regulation of nutrient and dissolved and particulate organic matter loadings
Phytoplankton	Marked horizontal gradients; volumetric primary productivity (or P_{max}) decreases from headwaters to dam, areal primary productivity relatively constant horizontally; light and inorganic nutrient limitations predominate	Vertical and seasonal gradients predominate; small horizontal gradients; light and inorganic nutrient limitations predominate
Bacterial heterotrophy	Pelagic, particle-associated and benthic bacterial heterotrophy predominates in riverine zones	Benthic and littoral/ wetland bacterial heterotrophy predominates in most lakes
Zooplankton	Maximal development common in transition zone; horizontal patchiness high; particulate detritus (including adsorbed DOM) variably augments phytoplankton as food source	Vertical and seasonal gradients predominate; horizontal patchiness moderate; phytoplankton is a perdominate food source
Benthic fauna	Low diversity with minimal and irregular littoral zone; productivity low to moderate; Initially high with inundated terrestrial vegetation	Moderate to high diversity; productivity moderate to high
Deposition of sediments	High in riverine zone, decreasing exponentially down-reservoir; greatest in old riverbed valley; highly variable rates seasonally	Low, limited dispersal relatively constant rates seasonally

Table C-1 (continued)

Properties	Reservoirs	Natural Lakes
Fish	Predominantly warm-water species composition; differences often related to initial stocking; spawning success variable (low with low water levels), egg mortality increases with siltation, larval success reduced with less refugia; productivity initially (5-20 y) high, then decreasing. Occasional two-story fishery (warm- and cold-water species) successful, particularly in mountainous reservoirs.	Warm-and cold-water species composition; spawning success good, egg mortality lower, larval success good; productivity moderate
Biotic community	Diversity low; niche specialization broad; growth selection rapid (r); Immigration-extinction processes rapid; net production high soon after inundation, then decreasing	Diversity high; niche specialization moderately narrow; growth selection variable, relatively homeostatic (K); immigration-extinction processes slow; production low to moderate, relatively constant
Ecosystem succession rate	Similar to lakes but greatly accelerated; greatly stressed by human manipulations of basin and drainage basin	Similar to reservoirs but greatly protracted

(Ref. C-6)

It is also useful to identify the differences between reservoirs used for hydropower and those used for other purposes. These differences often result in differing DO dynamics. Large hydropower projects (i.e., greater than 10 MW) tend to have the following characteristics when compared to reservoirs used primarily for other purposes:

1) Considerably higher flow-through rates than for reservoirs used only for water supply and recreation. The average annual flow rates for TVA projects range between 410 and 40,300 CFS.

2) Low-level or mid-level outlets compared to surface discharges or releases through multilevel outlets for reservoir projects commonly used for other purposes.

3) Less natural aeration in the tailrace compared with non-power projects because the turbines consume as much energy as is practical, leaving less energy dissipation in the tailrace and, thereby, reducing aeration.

4) Larger reservoirs, primarily because hydropower production is dependent on relatively higher flows and water head, which often translates into the need for greater storage volumes and depth of water leading to reservoirs with more surface area and length.

5) Typically, much greater water-level fluctuations than for reservoirs used for water supply and recreation. Also, the patterns of water level fluctuations tend to be annually systematic compared to reservoirs for some other uses, e.g., water supply and recreation.

6) Less need to design and operate projects to store water for long-term use (such as for irrigation and water supply in the arid west) because hydropower generation is a benefit even in climates where precipitation is abundant and exceeds evaporation.

These unique characteristics can have significant bearing on DO dynamics in reservoirs.

C.2 SYNOPTIC REVIEW OF DISSOLVED OXYGEN LITERATURE

The number of studies that have been conducted on the factors that affect DO in reservoirs has been too numerous to summarize here. At the same time, it is useful to review some literature to establish a basis from which to identify concepts and factors that affect hydropower reservoirs. Following is a review of the historical development of the understanding of DO dynamics in hydropower reservoirs, as well as a review of general concepts on water quality dynamics in

reservoirs that are applicable to hydropower projects. The next section presents a summary of the factors that should be considered in evaluating DO dynamics in reservoirs and their releases.

The first recorded DO studies on a hydropower reservoir were conducted in 1937 and 1938 on Norris Reservoir by Dr. A. H. Wiebe. His investigations lay much of the groundwork for understanding DO dynamics in reservoirs and, therefore, will be discussed more thoroughly than other studies.

Dr. Wiebe collected extensive data on DO, temperature, pH, alkalinity, turbidity, and DO uptake rates at various locations throughout Norris Reservoir, including some large embayments and lateral cross-sections at various locations up-reservoir from the dam.

Following is a summary of the most significant observations he made:

1) DO characteristics in the reservoir were two-dimensional with depth and distance upstream from the dam, with essentially no variations laterally across the reservoir (Ref. C-7).

2) Temperature essentially varied only with depth and, therefore, was one-dimensional, excluding near-field inflow dynamics (Ref. C-7).

3) In the forebay, low DO was first observed at the warmer portion of the metalimnion and near the bottom of the reservoir, in August, leaving relatively higher DO (4 to 6 mg/L) between these two depths until October when sufficient tributary inflow had entered the reservoir and sufficient volume of reservoir water had been released through the low level turbine outlets, resulting in the warmer portion of the metalimnion occupying more of the water depth as time progressed (Ref. C-7).

4) Early winter inflows, before destratification, entered the reservoir as underflow and carried high DO water below the thermocline (Ref. C-7).

5) In general, low DO at various locations throughout the reservoir was caused by the following factors (Ref. C-7):

    a) Uptake of DO from water above the sediments: depth of water above the sediments varying from 10 to 30 feet;

b) Uptake of DO in the warmer portion of the metalimnion which increased in volume throughout the summer as a result of the cumulative volume of inflow water extending into this area as interflow (with a temperature range of about 55° to 75°F);

c) The withdrawal of high DO water layered between the low DO water over the sediments and the low DO water in the warmer portion of the metalimnion, until this layer was depleted leaving only low DO water in the hypolimnion, as shown in Figure C-3.

6) He considered two factors for the explanation of low DO in the warmer portion of the metalimnion (Ref. C-7):

a) The first explanation considered was that the decrease in DO was attributed to the settling of biological products in the surface water. However, for the Norris project the decrease in DO was too pronounced to be caused by the biological processes observed. Also, ammonia concentrations and organic nitrogen concentrations gave no indication of such biological activity;

b) The likely explanation, according to Dr. Wiebe was a combination of factors involving the shallower and warmer water at the head of the reservoir and the even more important factor of organic detritus carried by the water from the tributaries. He reported that this detritus began settling out as it hit backwater at the head of the reservoir. The net result of the characteristics at the head of the reservoir was to yield low DO concentrations in the lower water depths at the head of the reservoir early in the summer, while at the same time retaining relatively high DO levels at the lower end of the reservoir where the water was colder and deeper and the effect of settleable material had little effect. As the summer progressed, the cumulative volume of water released through the turbines increased and the entire mass of water in the reservoir showed a tendency to move toward the dam. The colder and heavier water moved toward the outlet first and set up horizontal currents that moved more rapidly,

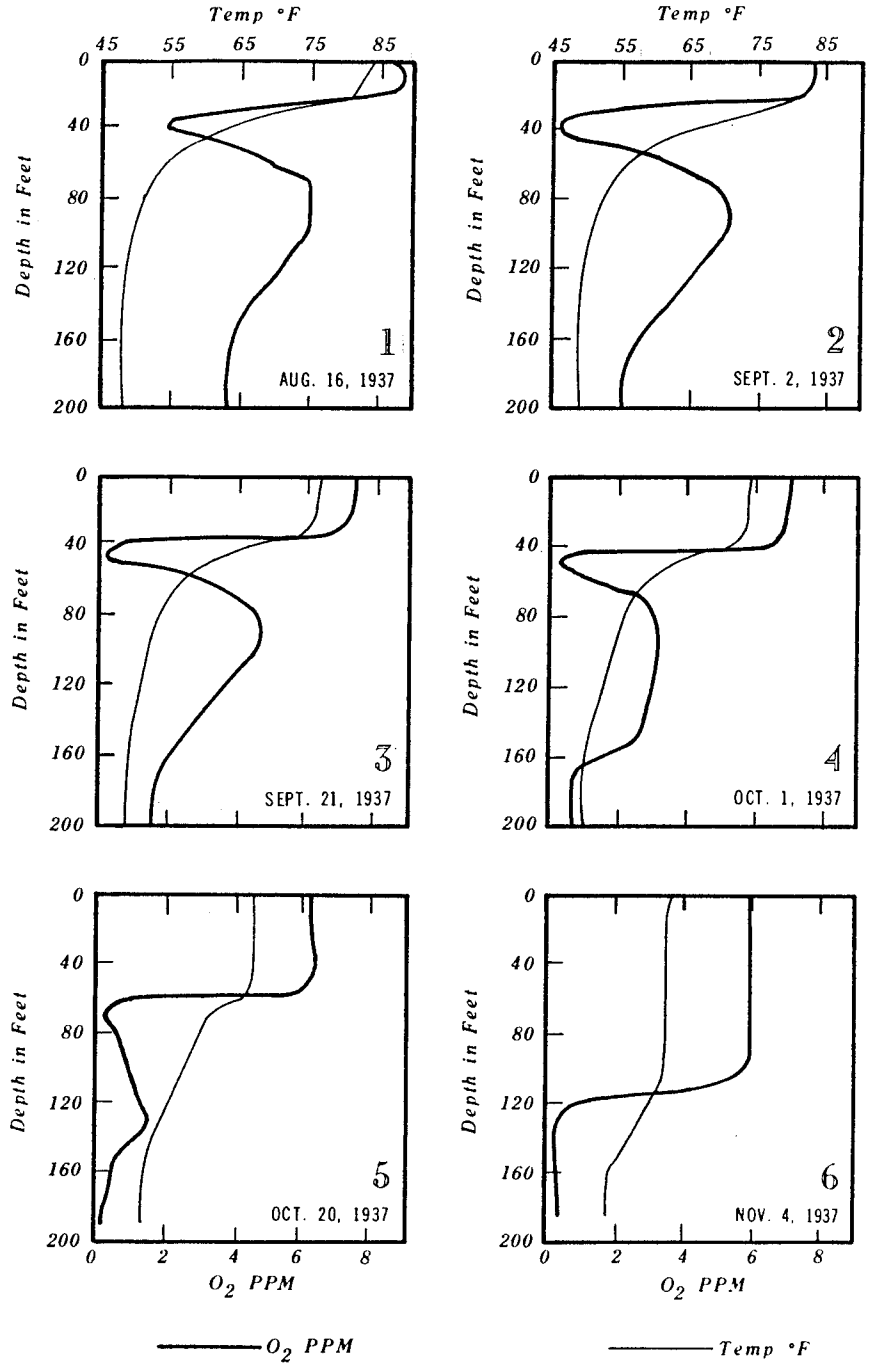


Figure C-3. Forebay DO and temperature observations on Norris Reservoir (Ref. C-7).

although very slowly, than the warmer waters above the elevation of the outlets. The withdrawal at the dam was strong enough to set up currents in the reservoir, but these currents were too weak to disturb the thermal stratification established throughout the reservoir. He noted that even in the absence of the withdrawal at the dam, that the interflow at the head of the reservoir would tend to spread throughout the reservoir, but that the release of water near the bottom of the dam exerted a profound influence upon the rate at which this interflow propagated over the entire reservoir.

7) Dr. Wiebe (Ref. C-8) conducted one study using measurements of the rate of DO uptake from samples of water collected at various depth at the head of a major tributary as well as at the mouth of the tributary which was about 18 miles downreservoir. The DO uptake rates were measured over a period of 7 to 15 days, were kept in the dark on a laboratory boat, and were subject to variations in temperature. Results of these studies were limited to only a comparative analysis between the DO uptake rates from the two stations. The results showed that the DO uptake rate at the upstream station was about 7 mg/L within 7 days compared with a DO uptake rate of only 1.4 mg/L over the same range of depth at the lower station. Other interesting observations were that the DO uptake in the upper 50 feet of water depth at the lower station was about 4.2 mg/L at 15 days compared to an uptake of only 2 mg/L in the water depths from 50 to 138 feet deep. Using these observations, Dr. Wiebe concluded that the metalimnion DO depletion at the lower station was at least in part influenced by the high DO uptake of the water in the interflow.

8) In addition to using the variation of temperature within the reservoir to explain the density currents, Dr. Wiebe offered additional proof that density currents were responsible for the low DO in the warmer portion of the metalimnion. He documented the movement of low alkalinity water from the head of the reservoir on a major tributary to the mouth of the tributary about 10 miles downstream. Also, on the main channel of the reservoir he traced several sub-surface strata of silt-laden waters and one of these strata was followed for a distance of 20 miles. He concluded that the DO in the metalimnion was a result of two factors:

a) The high biological oxygen demand in the water at the head end of the reservoir and the subsequent flow of this water as an interflow into the metalimnion, and

b) Density currents carrying this metalimnetic low DO water toward the dam at its characteristic density and temperature level.

9) He (Ref. C-9) concluded that although no actual measurements of density currents were made that the measurement of chemical and physical factors bore evidence for their existence. The apparent density currents were consistent with the collective interpretation of conditions in Norris Reservoir. Figure C-4 illustrates the variations in alkalinity in the interflow and Figure C-5 illustrates the variation of turbidity within the interflow.

10) Dr. Wiebe (Ref. C-10) also reported on the effect of higher inflow volumes during the year of 1938 on temperature and DO in Norris Reservoir. Differences in temperature and DO are shown in Figures C-6 and C-7. Figure C-8 illustrates the inflow volumes for the two years. In essence, during the latter year with higher inflows, the colder water in the bottom of the reservoir was released through the turbines at an earlier period of time in the year to accommodate the higher inflows. The summer inflow, therefore, resulted in occupying more volume of the hypolimnion and essentially resulting in warmer water moving to a relatively lower depth earlier in the year. The large amount of inflow during the wetter year resulted in lower DO at the dam earlier in the year than the previous year. The explanation for these lower DO in the wetter year was the higher amount of inflow of organic material and the warmer temperature. (It is interesting to note that similar observations on Norris Reservoir have been made during the 1980s.)

During the 1940s and 1950s, Milo A. Churchill and others at TVA conducted numerous studies on other reservoirs and contributed further to the understanding of density currents and low DO in reservoirs. Churchill's work covered a wide range of reservoirs within the TVA system and he provided many illustrations of how underflows and overflows affected DO within the reservoirs, particularly run-of-river reservoirs and transitional reservoirs. Many of these reservoirs were significantly affected by upstream wastewater

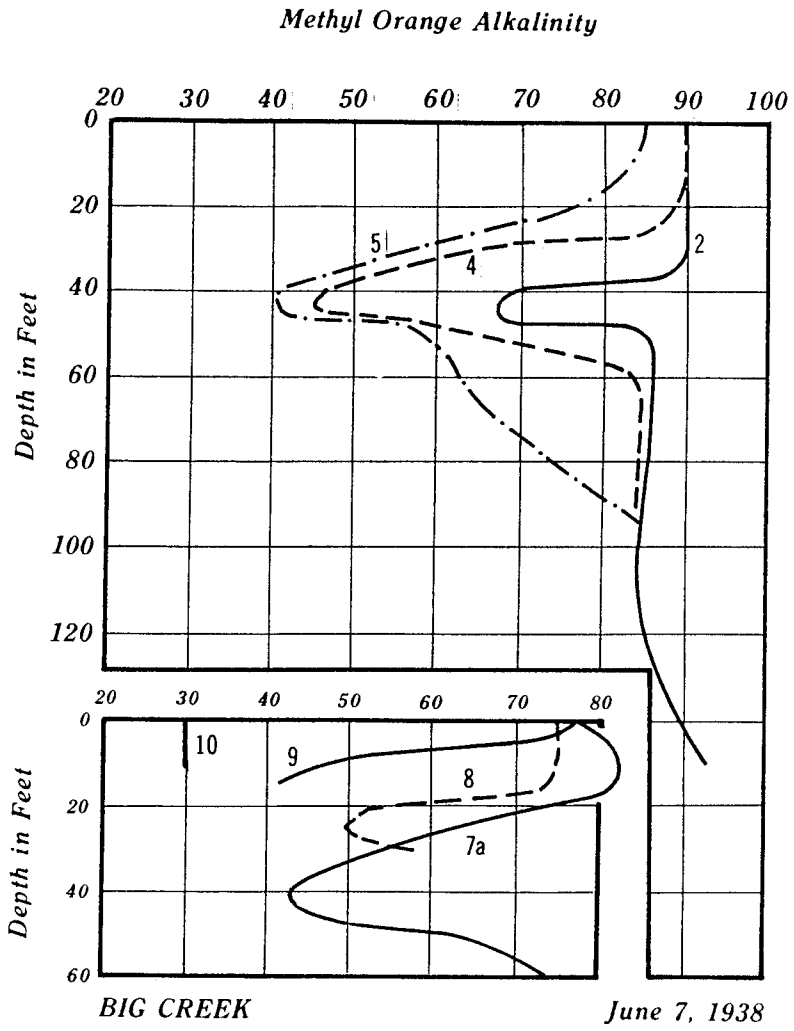


Figure C-4. Shows vertical distribution of methyl orange alklalinity in p.p.m. in Big Creek embayment of Norris Reservoir. The numbers on the curves denote stations, with the lowest numbers at the downstream end (Ref. C-9).

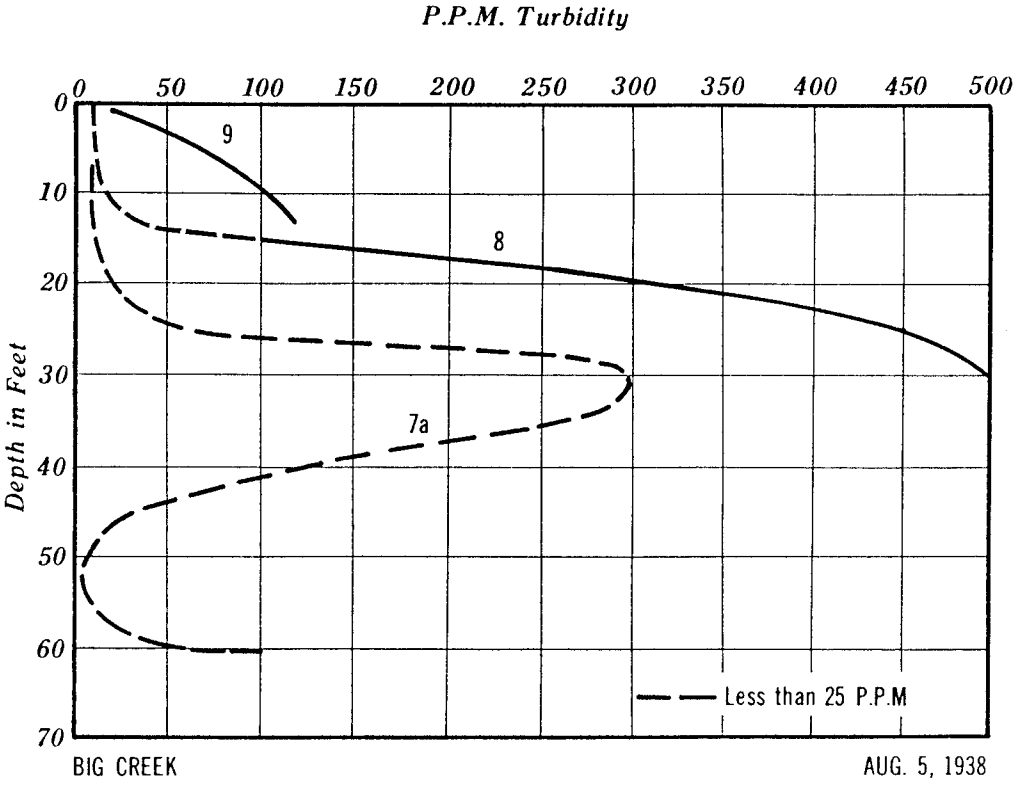


Figure C-5. Shows vertical distribution of turbidity in ppm in Big Creek embayment. The numbers on the curves denote stations. Numbers and locations as in Figure C-4 (Ref. C-9).

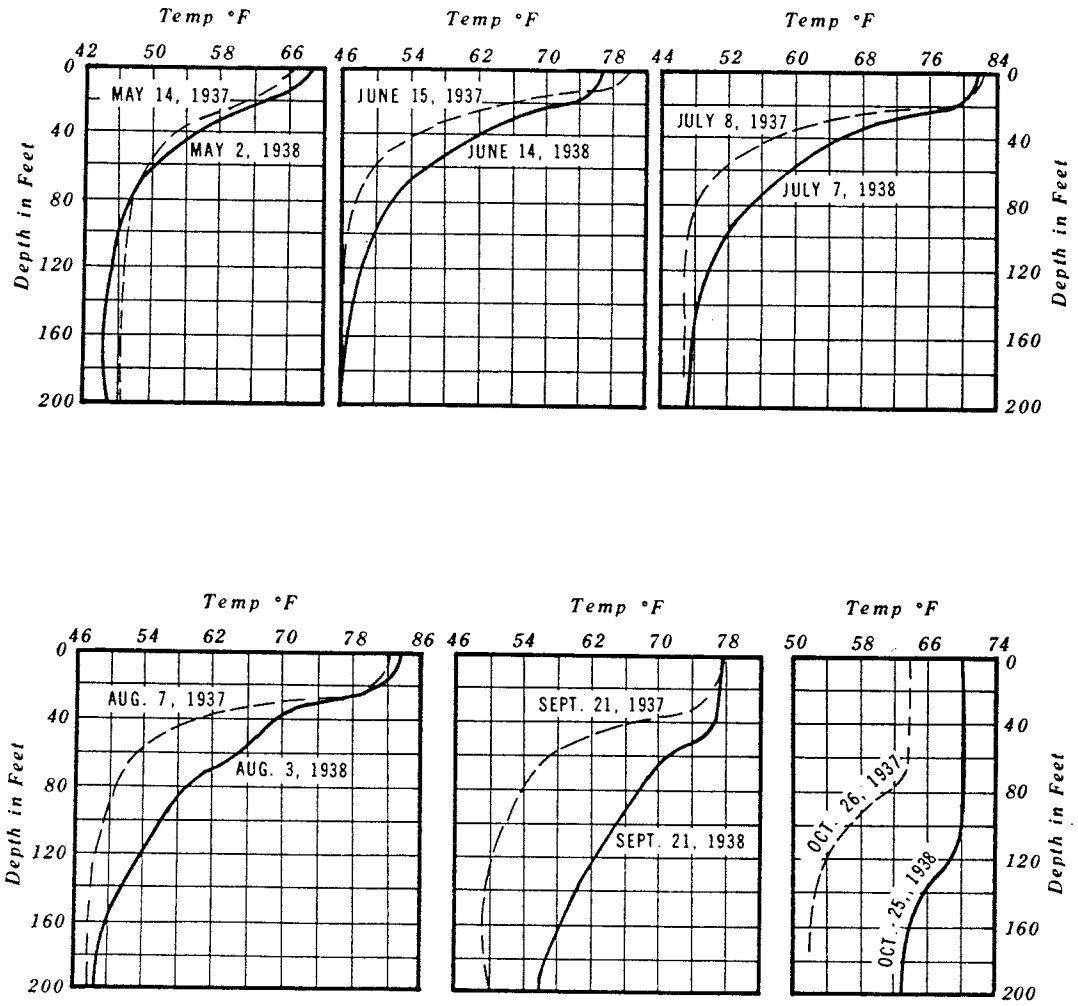


Figure C-6. Comparison of temperature for Norris Reservoir for May to October for 1937 and 1938. The profiles demonstrate the effects of higher inflows during the summer of 1938, showing how the colder water was released more rapidly and was replaced earlier in the year by warmer water (Ref. C-10).

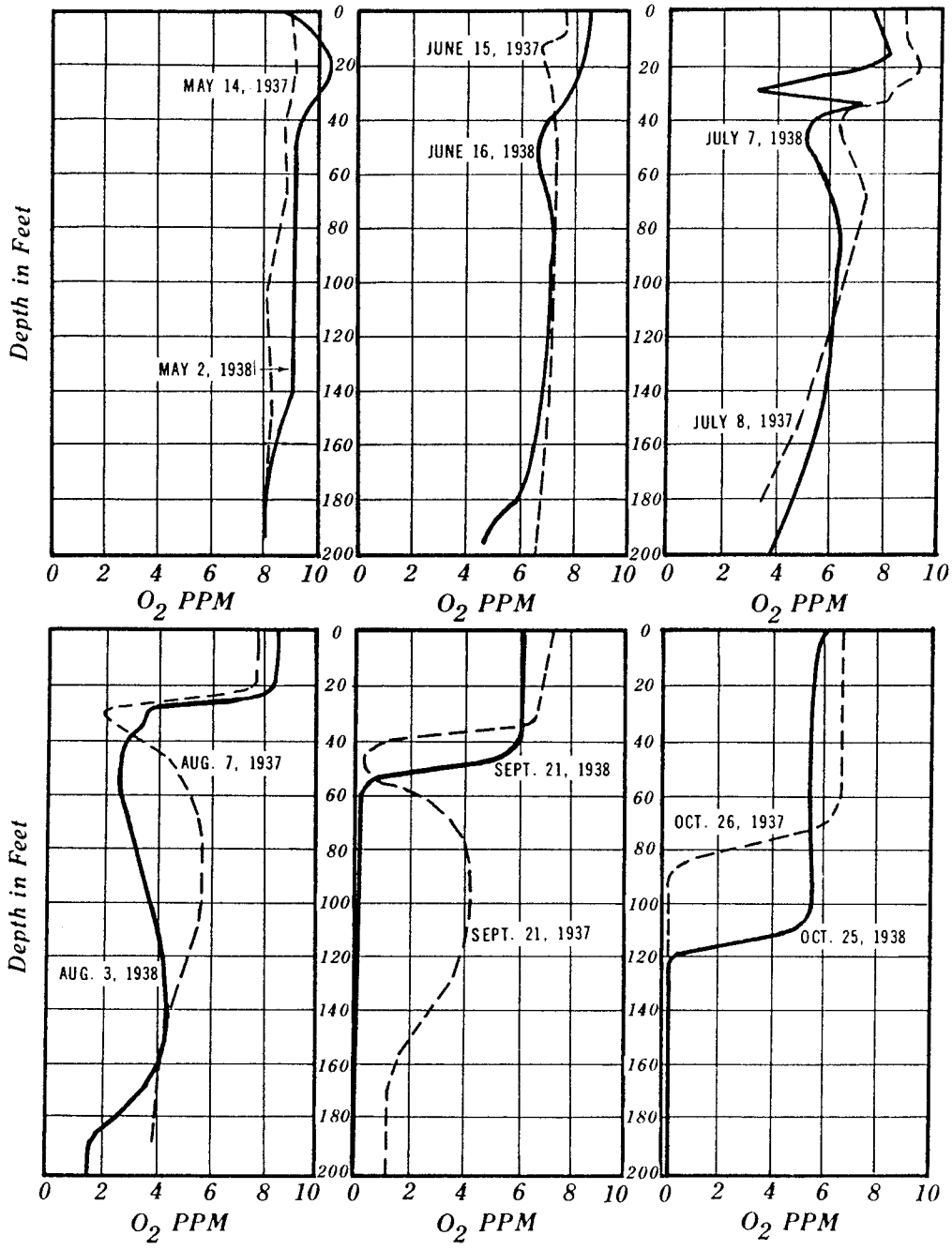


Figure C-7. Comparison of Dissolved Oxygen (p.p.m.) for Norris Reservoir from May to October for 1937 and 1938. The profiles show how low DO tracts the warmer density current as shown routed through the reservoir in Figure C-6 (Ref. C-10).

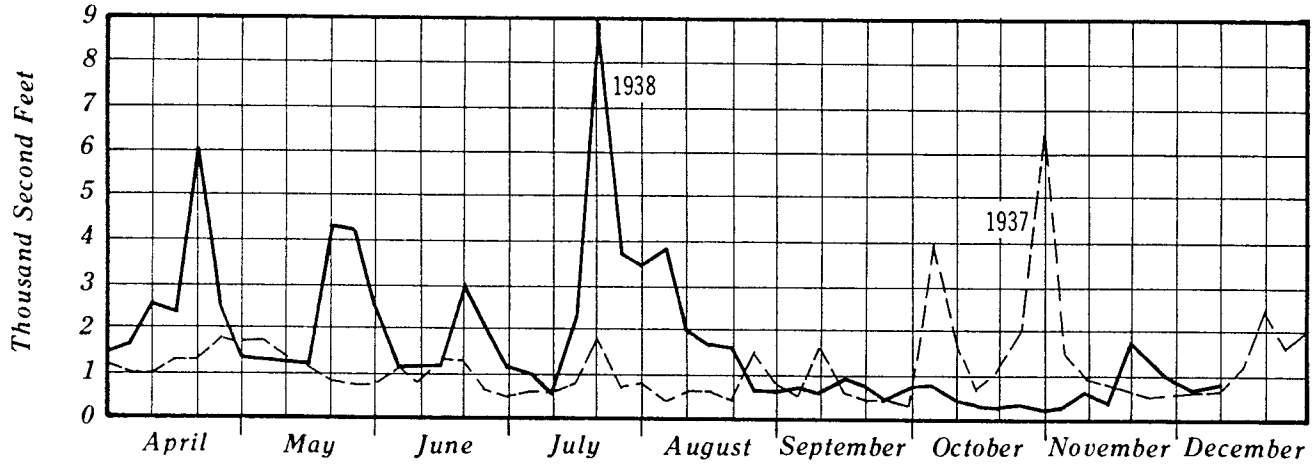


Figure C-8. Volume of flow in Clinch River above Norris Reservoir in thousand second feet from April 1 to October 31 for 1937 and 1938 (Ref. 3-10).

discharges from municipalities and industries, at a period of time when wastewater treatment levels were significantly less than they are today. However, he illustrated for several projects how the sediment oxygen demand was a significant factor in the DO balance for relatively clean reservoirs. He also pointed out that there was sufficient "natural pollution" included in the inflow waters to lower DO in the turbine releases to approximately zero in the late summer. For example, he reported that the watersheds of Nottely and Chatuge Reservoirs had no municipal or industrial wastewater discharges and that the watersheds of the Watauga and Norris Reservoirs had only minor quantities (these watersheds also had relatively low known amounts of man-induced nonpoint sources). Yet, in the midsummer of every year each pool produced water that showed a DO concentration of less than 2 mg/L.

Churchill (Ref. C-11) summarized the various density overflows and underflows that occur in reservoirs. Of course the occurrence of such flows is dependent on the temperature of the receiving reservoir as well as the inflow temperature. Churchill also reported extensively in his publication on the density currents in reservoirs downstream from storage impoundments. As one would suspect, underflows are quite typical in such situations due to the cold, or at least cooler, temperature in the releases from the upstream projects. Such underflows even occur for the warm water releases that occur in the Tennessee River on the mainstem projects. On mainstem projects, typical temperature and DO profiles form a wedge upstream from the dam that persists for approximately for half the distance of the reservoir (see Figure C-9).

Higgins and Fruh (Ref. C-12) reported on DO dynamics in a relatively unpolluted deep storage impoundment in central Texas. Lake Travis has an operating capacity of 1,170,000 acre feet and is used for flood control and hydroelectric power generation. Their studies showed that the metalimnion had a DO of near zero at a depth of 60 feet and that the lower depths of the reservoir down to 140 feet had a DO concentration of 2 mg/L. They, like Wiebe, considered the effect of phytoplankton in the epilimnion and the resulting sinking

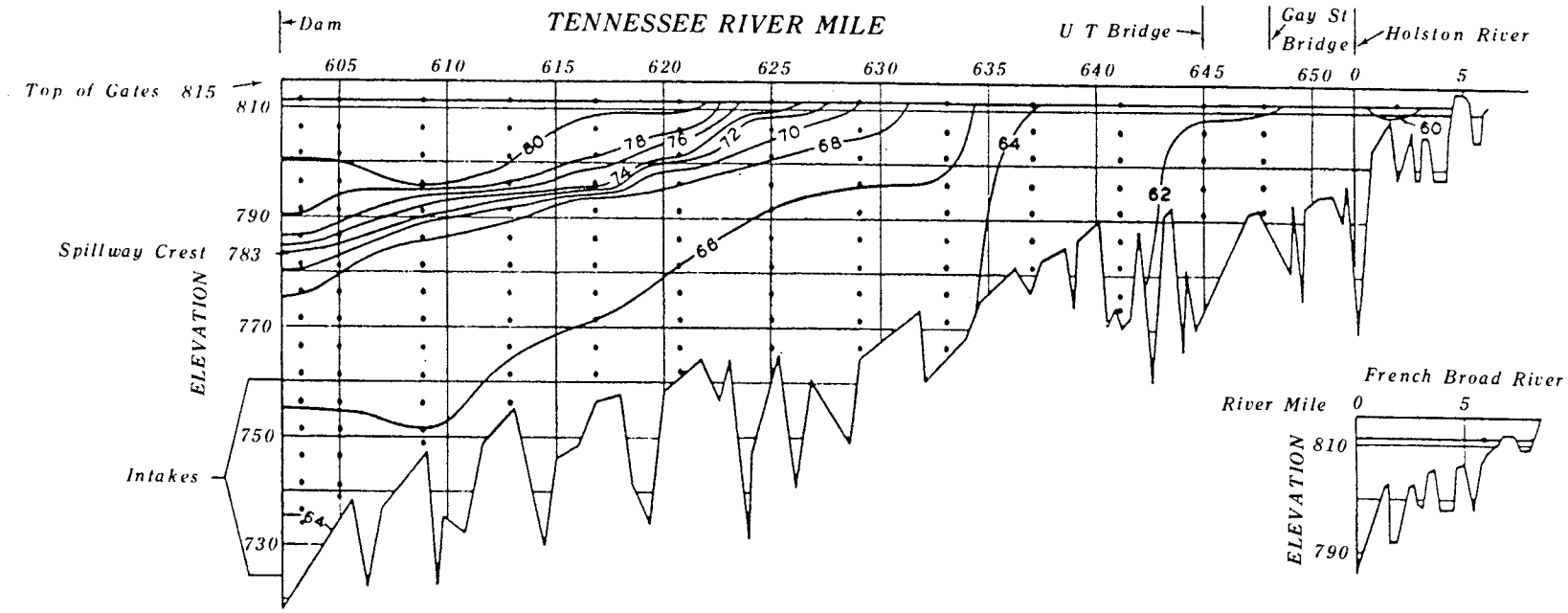


Figure C-9. Water temperatures in Fort Loudoun Reservoir - July 20-21, 1944. Demonstrates the longitudinal nature of thermal stratification in a typical mainstream reservoir (Ref. 3-11).

organic material into the upper metalimnion. However, they reported that the quantity of phytoplankton in the epilimnion was quite small.

In addition, algae were found at all depths, even in the lower hypolimnion. Light measurements at depths as great as 100 feet were reported to be about one percent of surface light. Therefore, the oxygen depletion in the metalimnion was not attributed to sinking dead phytoplankton alone. They also considered density currents, but reported that they found no changes in turbidity, color, conductance, or other parameters that may indicate the occurrence of a density current. They reported that the impoundment was relatively unpolluted and was not considered to be eutrophic and that in southwestern impoundments it appeared that trophic status as commonly applied to lakes could not be reliably used as an indicator of DO conditions. Chendler (Ref. 3-31 and 3-32) and Ruane (Ref. 3-33) also reported on DO dynamics in reservoirs upstream and downstream from Lake Travis.

Wunderlich (Ref. C-13) summarized various field investigations to measure the peculiar water movements in large reservoirs used for hydropower production, due to various conditions of inflows (overflow, interflow, and underflow), outflows, and other causes such as solar radiation absorption. the relationship between reservoir hydrodynamics and reservoir water quality was discussed. Figure C-10 illustrates the types of inflows. Figure C-11 provides an assessment of how upstream/downstream velocities occur within a reservoir when an interflow occurs in combination with intermittent hydropower releases at the dam through low-level outlets. Wunderlich also presented results of solar radiation measurements on three reservoirs (Figure C-12) and 6-hourly temperature data at the on-set of stratification to illustrate how the density-layer process begins in an actual case study (Figure C-13).

Gordon (Ref. C-14) reported on DO depletion mechanisms in Center Hill Reservoir (Tennessee), a storage impoundment used for hydroelectric power. The project experienced a 50-foot layer of reservoir water in the metalimnion where the DO became totally depleted. His study showed that the mechanism having the greatest impact on DO was phytoplankton and zooplankton respiration. He reported that temperature related density-viscosity gradients in the metalimnion resulted

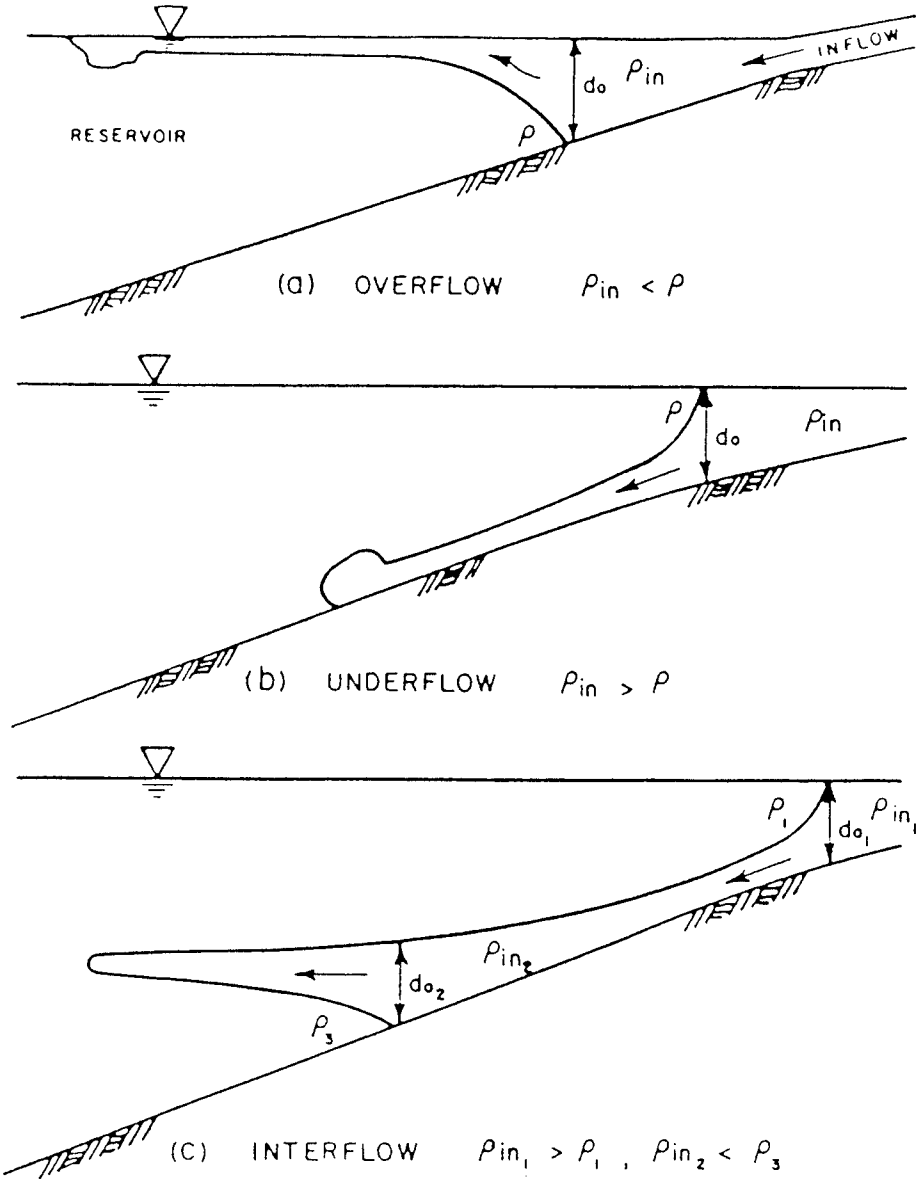


Figure C-10. Types of inflow into reservoirs (Ref. C-13).

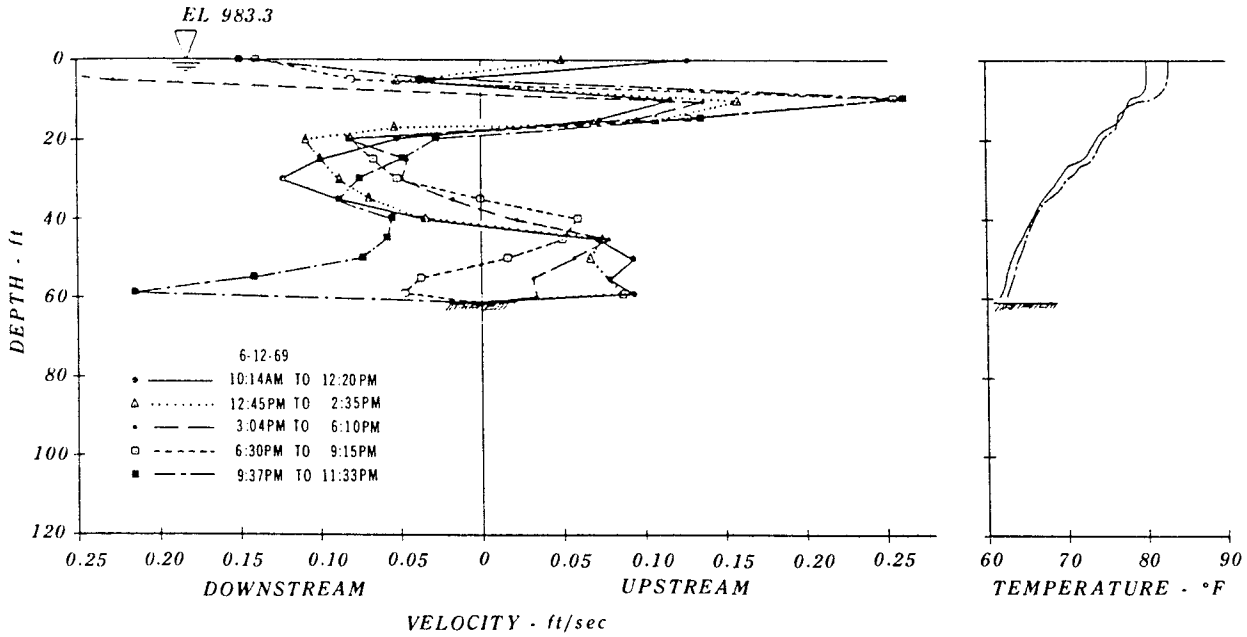


Figure C-11. Unsteady internal water movements in Douglas Reservoir, Tennessee (Ref. C-13).

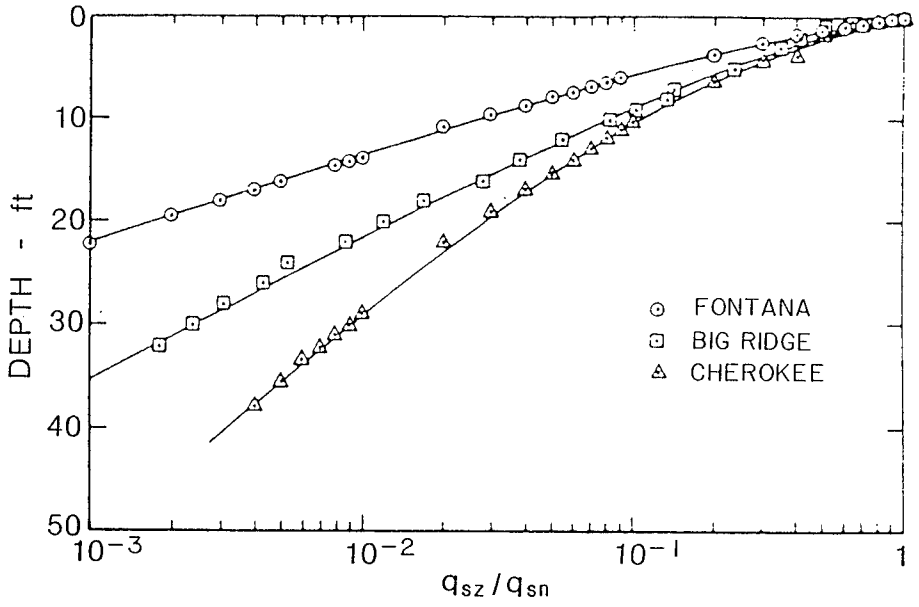


Figure C-12. Ratio of solar radiation at a certain depth below the water surface to the solar radiation penetrating the water surface (Ref. C-13).

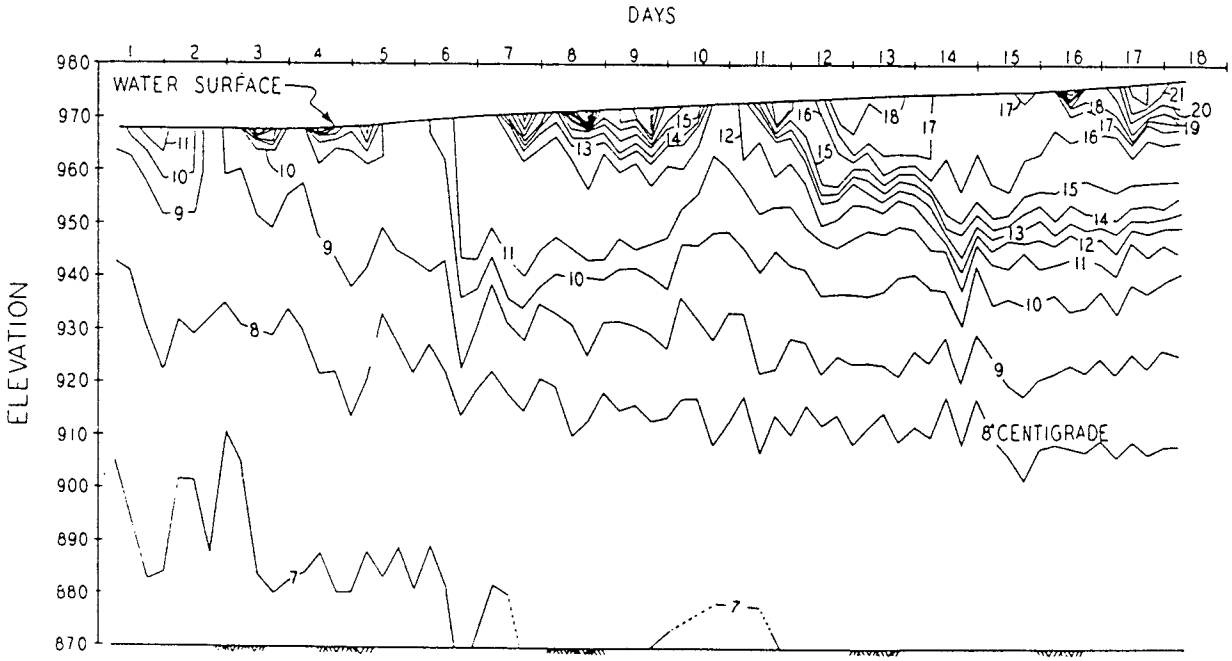


Figure C-13. Six-hourly temperature variations in April 1969 in Douglas Reservoir, Tennessee (Ref. C-13).

in differential settling velocities and these caused significant increases in chlorophyll-a concentrations in the metalimnion. The phytoplankton produced or consumed DO, depending on the depth of the photic zone. An earlier review of the literature by Gordon reported that oxidation of falling materials slowed by temperature gradients contributed to DO depletion but is not a major mechanism except for lakes that are highly fertile and turbid. He presented models for calculating the photosynthesis and respiration for chlorophyll-a and other biological organisms found in reservoirs. Gordon also calculated the DO uptake by other various mechanisms one of which was the 28-day BOD. However, BOD samples were collected from within the main body of the reservoir and may not have accounted for organic material oxidized between the point of inflow and the BOD sampling point.

Hannan (Ref. C-15) reported on another lake in Texas, Canyon Reservoir, which was not used for hydroelectric power generation. The DO dynamics of this reservoir was shown to be a function of DO uptake primarily in the upper reservoir reach. He reported observations similar to those by Wiebe. He reported on the effect of a drought year during which the inflow and the outflow at Canyon Dam was at a minimum. He reported that the down-reservoir development of the anoxic hypolimnion occurred but it had not developed by the end of July as far down-reservoir as it had in July the year of higher flows (1976). Hence, between the papers by Wiebe and Hannan, it can be envisioned that during hydrologic wet years, the progression of low DO is much further down-reservoir and during drought years the progression of low DO down-reservoir is not as great. Between the two reservoir studies by Wiebe and Hannan it can be concluded that density currents are an obvious contributor to low DO levels seen in metalimnions at down-reservoir locations. (This conclusion is supported by DO data collected during the drought years of 1986 and 1988 in the Tennessee Valley, based on forebay profiles collected at most of TVA's reservoirs.) Nix (Ref. 3-34) also reached this conclusion on DeGray Reservoir in Arkansas.

Thornton, et al. (Ref. C-16), suggested a conceptual, heuristic model to capture in a generic fashion the experience up to that time and to stimulate further investigation to test the model. Following is an excerpt from their paper that describes the model:

Morphologic differences between lakes and reservoirs and the importance of sedimentation form the basis for a conceptual model to describe and explain the development of longitudinal gradients in reservoirs. Although occurring along a continuum from river inflow to dam, these gradients result in the establishment of three distinct zones possessing unique physical, chemical, and ecological properties. These three zones are a riverine zone, a zone of transition, and a lacustrine zone. Although velocities in the riverine zone are decreasing, this zone is relatively narrow, well mixed, and advective forces are still sufficient to transport significant quantities of finer particles, such as silts, clays, and organic particulates. Light penetration is minimal and generally limits primary production. An aerobic environment is maintained because the riverine zone is generally shallow and well mixed, even though the degradation of allochthonous organic loadings often creates a significant oxygen demand. Secondary production in this portion of the reservoir would be subsidized by allochthonous material through detrital food chains.

Significant sedimentation occurs through the transition zone with a subsequent increase in light penetration. Light penetration may increase gradually or abruptly, depending on flow regime. If an overflow occurs, light penetration will increase gradually down the reservoir as sedimentation occurs. If the inflow proceeds as an inter- or underflow, light penetration in the mixed layer will increase abruptly downstream of the plunge point, a point where sediment-laden inflowing water sinks to a depth of comparable density. At some point within the mixed layer of the zone of transition, a compensation point between the production and processing or organic matter should be reached. Beyond this point, autochthonous production of organic matter within the mixed layer should begin to dominate.

The lacustrine zone is characteristic of a lake system. Sedimentation of inorganic particulates is low, light penetration is sufficient to promote primary production with the potential for nutrient limitation and production of organic matter exceeds processing within the mixed layer.

Entrainment of metalimnetic and hypolimnetic water, particulates, and nutrients may occur through internal seiches or wind mixing during the passage of large weather fronts. Hypolimnetic mixing may be more extensive in reservoirs because of hypolimnetic or bottom withdrawal. Bottom withdrawal removes hypolimnetic water and nutrients, and may promote movement of inter- or underflows into the hypolimnion.

They then discussed prototype projects, i.e. West Point in Georgia, Livingston Reservoir in Texas, and Lake Powell in Arizona. Similar

dynamics have been reported for Norris and Cherokee Reservoirs in the TVA system and Canyon Lake in Texas.

Miller (Ref. C-17) presented information on reservoir limnology for two western intermountain projects, one of which was a hydropower project, Flaming Gorge. Flaming Gorge has a long retention time of 2.4 years, a length of 150 kilometers, and a maximum depth at the dam of 135 meters. He presented information in the context of the heuristic model by Thornton, et al. Figure C-14 illustrates the conditions in Flaming Gorge Reservoir, showing low DO in the upper riverine and transitional zones and high DO in the lacustrine zone. The high DO in the lacustrine zone is thought to be related to the large volume and long retention time, resulting in relatively less effect of summer interflows. The reservoir exhibited significant down-reservoir trophic segmentation.

The releases from Flaming Gorge Reservoir do not have a low dissolved oxygen concentration, probably related to the low DO water near the inflow not being transported to the dam before the fall and winter turnover mixes the reservoir. Miller discussed the significance of eutrophication in the inflow zone of the reservoir. He reported that a number of factors contribute to the development of noxious blue-green algae in this zone. The factors include natural phytoplankton pulses in the inflow streams, the mixing of phosphorus released from the sediments in the anoxic portions of the inflow and the subsequent fall turnover, watershed erosion and agricultural nonpoint sources, municipal point sources, high phosphorus releases from an upstream reservoir, and the hydrometeorological dynamics at the inflow area. He stated that the fishery in this area, although occasionally impacted, is very significant. Many other fishery limnologists report similar observations. However, in this case he reported that reducing or eliminating the dominance of the blue-green algae would be much more desirable than reducing the total productivity or trophic status of the entire reservoir. He also stated that the length of the eutrophic zone in a reservoir inflow area should be considered before locating recreational facilities.

Kennedy, et al. (Ref. C-18), presented an excellent overview of the hydrological and ecological factors that affect reservoir water

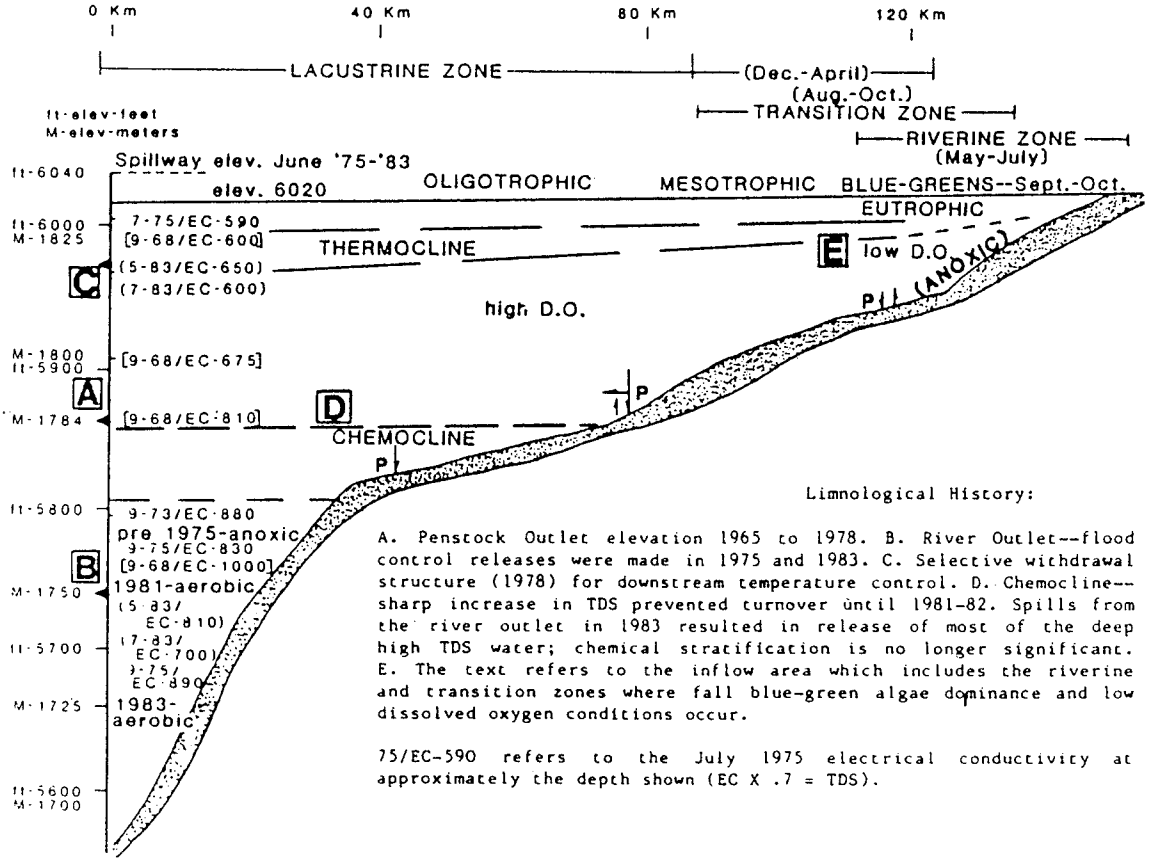


Figure C-14. Flaming Gorge Reservoir limnological profile (Ref. C-17).

quality, including DO. The paper addresses the characteristics of watersheds and their contribution to effects on reservoir water quality (including discussion on the sources of organic materials). They also presented a review of the literature of inflow mixing processes and reservoir mixing, i.e. the latter mixing related to the effects of wind across the reservoir surface and the unsteady nature of hydropower peaking and its resulting effect of internal momentum waves within the reservoir.

Hannan and Cole (Ref. C-19) prepared an extensive review of the literature on DO dynamics in all types of reservoirs, including those used for hydropower production. Their review was comprehensive in terms of the factors that affect DO as well as comprehensive in the literature surveyed. The review included information on items such as source of oxygen, effects of temperature on DO dynamics of reservoirs, effects of flows at various points within a reservoir system, the effects of density currents, morphology, allochthonous inputs, autochthonous inputs, photosynthesis and respiration, and the effects of wind. They then presented a discussion on the general pattern for hypolimnetic oxygen depletion in reservoirs followed by a discussion on DO in the metalimnion. With respect to metalimnion DO, they discussed the effects of interflows, the persistence of low DO values within the metalimnion because of its isolation from the photic zone, the high biochemical oxygen demand that can be associated with interflow, particularly during flood events. They also discussed the possibility of oval circulation patterns in the epilimnion during summer stratification causing an internal cell of stagnant water. A DO minimum could occur in such an isolated cell of water over time. They suggest that the controlling factors in minimum DO occurring in metalimnions appear to be the interflow and decomposing seston, or "organic snow", settling below the euphotic zone into the metalimnion. They go on to discuss various circumstances that may occur within reservoirs that can cause unusual DO profiles within a reservoir.

Two dimensional computer models have been used over the past five years to simulate DO in reservoirs and these modeling efforts have significantly improved the understanding of DO dynamics within reservoirs, particularly hydropower reservoirs. Models are especial-

ly useful in identifying the key factors within a reservoir that affect DO and simulating DO for various reservoir operating conditions. When one is first confronted with attempting to understand the factors that affect DO variation within a reservoir, he is faced with numerous variables and factors that can possibly affect the DO; however, models can narrow down the range of variables to usually between 1, 2, or 3 key factors that can then be more directly evaluated to assess potential for improving or modifying DO patterns. Hauser (Ref. C-20) has been associated with the development and application of two dimensional models at 8 TVA reservoirs and several reports are available upon request. Brown (Ref. C-21) also has been associated with several two dimensional modeling efforts and has information available on his activities. Martin and Wlosinski (Ref. C-22) summarizes the results of their application of a 2D and 1D model to DeGray Reservoir in Arkansas. Martin (Ref. C-23) using a two-dimensional model developed by the Corps of Engineers determined that in DeGray Reservoir the metalimnion low DO in the lacustrine zone was caused primarily by transport of low DO water into the zone, from the transitional zone where DO was essentially consumed by sediment oxygen demand, dissolved organic material decay, algal respiration, nitrification, and detritus decay. Considerable research has been conducted at DeGray Reservoir and in 1987 a symposium was held to summarize all of the research conducted on this reservoir. The proceedings from the symposium were published (Ref. C-24). Cole (Ref. C-25) is upgrading the 2D model used by the Corp of Engineers.

C.3 RECOVERY OF DO IN TAILWATERS / CASE STUDIES

DO concentrations in the tailwaters of hydroprojects can experience extreme variability with time and with distance downstream from the release. Insight into cause-effect can be obtained by recognizing that the DO concentration at any location in the tailwater is the result of a balance of competing processes that act as either sources or demands of DO in that reach. If the combined rates of the sources exceed the rates of the demands, the DO concentration will increase. The rate of each DO source or demand usually changes overtime and distance as a result of environmental conditions such as flow,release quality, and meteorology.

This process rate perspective is illustrated by using a simple mass balance to compare rates in a typical reach as follows:

$$\underline{\text{Rate of change in DO}} = \underline{\text{Inflow}} - \underline{\text{Outflow}} + \underline{\text{Reaeration}} - \underline{\text{Sedi-ments}} + \underline{\text{Aquatic plants}}$$

$$dO/dt = Q_{in}O_{in}/V - Q_{out}O/V + K_2(O_s-O) - S/h + (P-R)/h$$

$$- \underline{\text{Decay}} - \underline{\text{Dilution}}$$

$$- K_d\,L - K_n\,N - (O/V)\,dV/dt$$

where:

O = DO concentration in the reach
dO/dt = rate of change of DO in reach
V = volume of water in reach
Q_{in} = inflow rate
O_{in} = DO concentration of the inflow
Q_{out} = outflow rate
K_2 = reaeration rate
O_s-O = DO deficit below saturation concentration (O_s)
S = areal oxygen demand rate of organic sediments
h = mean depth
$P-R$ = areal rate of photosynthetic oxygen production in excess respiration from aquatic plants
K_d = deoxygenation rate of carbonaceous BOD
L = carbonaceous BOD concentration
K_n = deoxygenation rate of nitrogenous BOD
N = nitrogenous BOD concentration
$(O/V)\,dV/dt$ = rate of DO change due to dilution

More complete mass balances can be formulated, but this equation captures the major influences for many tailwater studies. This equation can be used to roughly compare the various DO processes by considering some typical values of the variables. For a vegetated reach immediately downstream from a large hydroproject with no large tributary or pollution sources, variables in the above mass balance equation might typically appear with values as shown in Table C-2 (for 1-unit discharge of a large hydroplant into a TVA tailwater reach during daytime hours). Inflow, outflow, natural reaeration, and plant photosynthesis and respiration are seen to have rates one to two orders of magnitude larger than other processes during the day for this reach. As inflow is increased above this level, its effect begins to overwhelm the instream processes. As flow is decreased, such as between turbine generating periods, the effect of instream processes become more pronounced. Numerous mechanistic formulations

Table C-2

COMPARISON OF DO SOURCES AND DEMANDS

Reach Characteristics:

Reach length	10	km
Reach depth	1	m
Reach width	100	m
Reach volume	10^6	m^3
Q_{in}, Q_{out}	100	m^3/s = 8.6E6 m^3/day
O_{in}	1	mg/L
O	2	mg/L
O_s	9	mg/L
K_2	2	1/day
SOD	1	gm O_2/m^2/day
P (daytime)	30	gm O_2/m^2/day
R	10	gm O_2/m^2/d
K_d	0.1	1/day
L	3	mg/L
K_n	0.3	1/day
N	2	mg/L

Process	Mass Balance Term	Rate mg O_2/L/day
Inflow DO	$Q_{in}O_{in}/V$	8.6
Outflow DO	$Q_{out}O/V$	-17.2
Natural reaeration	$K_2(O_s-O)$	14.0
Sediment oxygen demand	SOD/H	-1.0
Photosynthesis/respiration	P-R/h	20.0
Carbonaceous BOD decay	K_d L	-0.3
Nitrogenous BOD decay	K_n N	-0.6

for various terms and rates in the mass balance equation for riverine DO predictions can be found in a comprehensive review by Bowie, et al. (Ref. C-26).

Case Examples Of DO Variability And Recovery In TVA Tailwaters

Cherokee Tailwater. Cherokee Dam is a large 4-turbine hydropower project on the Holston River with a total generating capacity of 130 MW. Each turbine normally discharges about 4,000 CFS. Cherokee tailwater extends 52 miles (slope 2.4 ft/mile) from the dam to the confluence of the Holston and French Broad Rivers at the headwaters of Ft. Loudoun Reservoir. Tailwater conditions are characterized by an extremely variable flow regime due to hydrogeneration superimposed

on a highly vegetated channel with moderate temperature, very low DO water in summertime releases and low BOD from background or local sources.

Comparison of the magnitude and timing of flow and DO changes provides insight into temporal DO variations in the tailwater. Figure C-15 shows measured temperature and DO variations with associated flows during late July, 1982 at a location 7.4 miles downstream from Cherokee Dam. Generation at Cherokee Dam was 4-units (17,000 CFS) from 11 am to 11 pm each day, except for a 36-hour period of 1-unit generation (4,000 CFS) from 12 noon on July 24 through 12 midnight on July 25.

The combined influences of flow regime, natural reaeration, aquatic plants, and release DO are all vividly demonstrated in these data. At the beginning of July 24, flow has been at 17,000 CFS for several hours and DO is 1-2 mg/L, indicating very little reaeration due to very short travel time from the dam (recall the release DO was 1 mg/L or less). As flow decreases in the first 6 hours of July 24, DO increases due to greater reaeration (shallower depths, longer travel time) between the dam and the data station. However, around 8 am DO increases very rapidly from the added influence of plant photosynthesis as daytime solar radiation increases. Increasingly shallower depths exaggerate the photosynthetic effect because the volume of water in the channel becomes very small. This allows DO to become supersaturated to about twice the saturation concentration (note that saturation DO at 15°C is about 10 mg/L). The shallow depths also allow a sharp rise in temperature from solar heating. When 1-unit flow arrives in the late afternoon of July 24 and the low DO volume carried in this release overwhelms plant photosynthesis, DO drops sharply to about 6 mg/L. As nighttime progresses and the photosynthetic contribution disappears, DO drops to about 2.5 mg/L. Thus, DO reaerates from about 1 mg/L to 2.5 mg/L in 7 miles at 1-unit flow, compared to reaeration from 1 mg/L to 1.5 mg/L at 4-unit flow. The slightly shallower depths and longer travel time at 1-unit flow compared to 4-unit flow provide more opportunity for a deaerated particle of water to be mixed to the surface and reaerated.

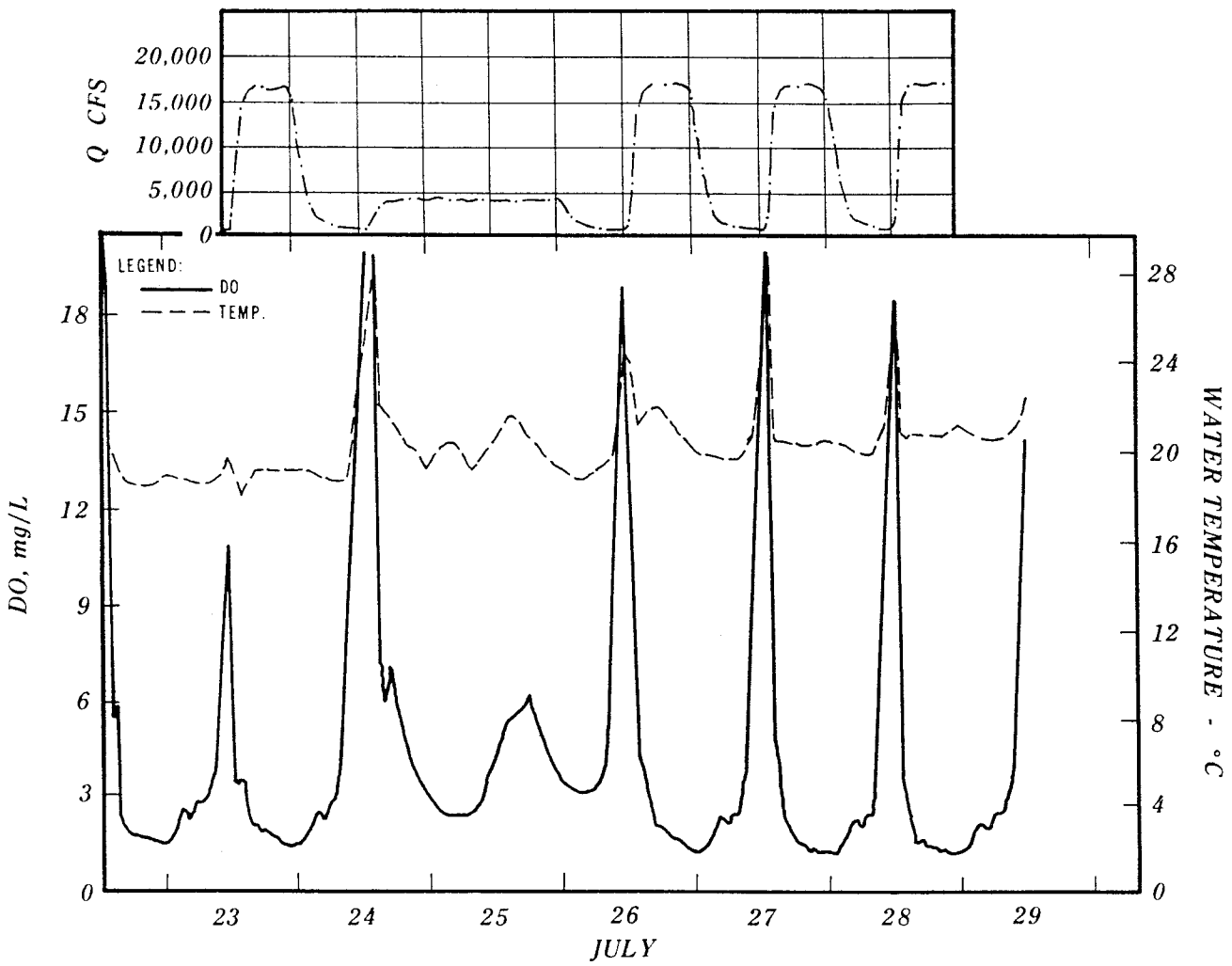


Figure C-15. Temporal temperature and DO variability 7.4 miles downstream from Cherokee Dam.

The 36-hours of steady 1-unit flow was discharged specifically to allow the effects of diurnal plant processes to be isolated from any complicating effects of flow changes. Thus, the increase in DO from 2.5 mg/L on the morning of the July 25 to just over 6 mg/L by mid-afternoon is purely the effect of plant photosynthesis on DO at 1-unit flow. Note that at this flow, aquatic plant effects on DO concentration are much diminished (3 to 6 mg/L) compared to the 3 to 20 mg/L effect during low flow the previous day, but the volume of water affected is greater. Remaining variations in DO (July 26-28) are due to interaction of processes previously described for July 24.

A dynamic river water quality model, described by Hauser, et al. (Ref. C-27) was calibrated to the July 1982 survey data and used to present how the major DO process rates varied with time during the survey in a pool and in a riffle location. Figure C-16 shows the rates of photosynthesis, respiration, and reaeration normalized to gm O_2/m^2/day for each. Reaeration is greatest in shallow, high velocity reaches during low flows and can become negative due to supersaturation during periods of high photosynthetic effect on DO (daytime, low flow). The effects of all processes tend to be dampened in deep pools and increased in shallow reaches.

The model was also applied to simulate worst case longitudinal DO patterns. Late summer release DO represents a seasonal minimum, so the worst case DO distribution is generated by a prolonged high discharge during this period. Figure C-17 shows simulated DO (diurnal minimum, mean, and maximum) in the Cherokee tailwater for steady 1-unit and 4-unit discharge with a release DO of 0 mg/L. The general upward trend in the DO, asymptotic to a saturation DO of 9 mg/L reflects the influence of natural reaeration. The maximum and minimum lines indicate the range of diurnal variation due to photosynthesis and respiration. At higher discharges, daily DO fluctuations due to photosynthesis are reduced but not eliminated. Minimum DO concentrations from the steady flow simulation represent the lower bound of DO concentrations from any unsteady flow simulation, except in certain cases where plant respiration in predawn hours during a turbine shutoff period can drive DO concentrations even lower.

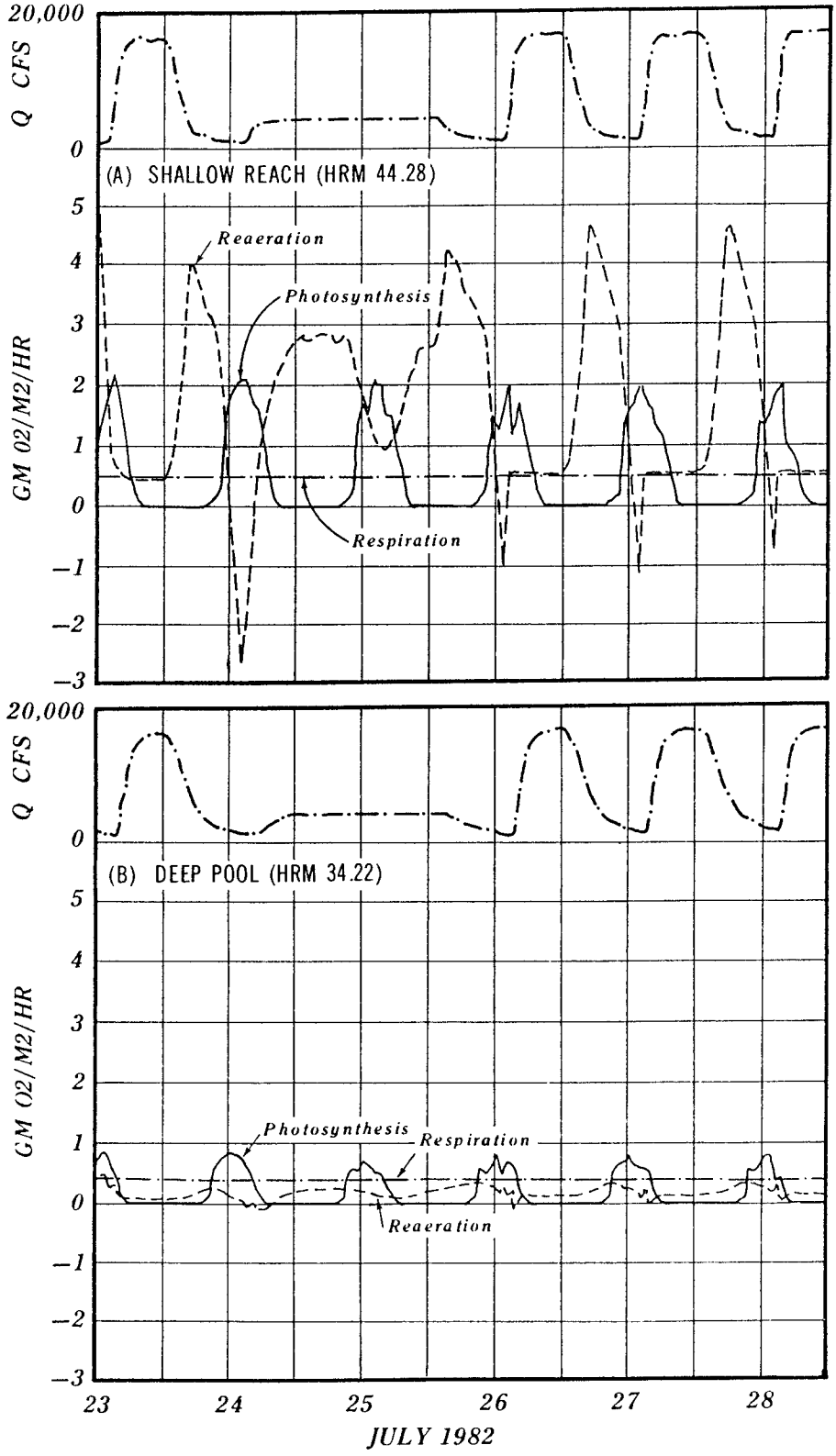


Figure C-16. Modeled Variability in DO process rates in a pool and riffle location in Cherokee Tailwater.

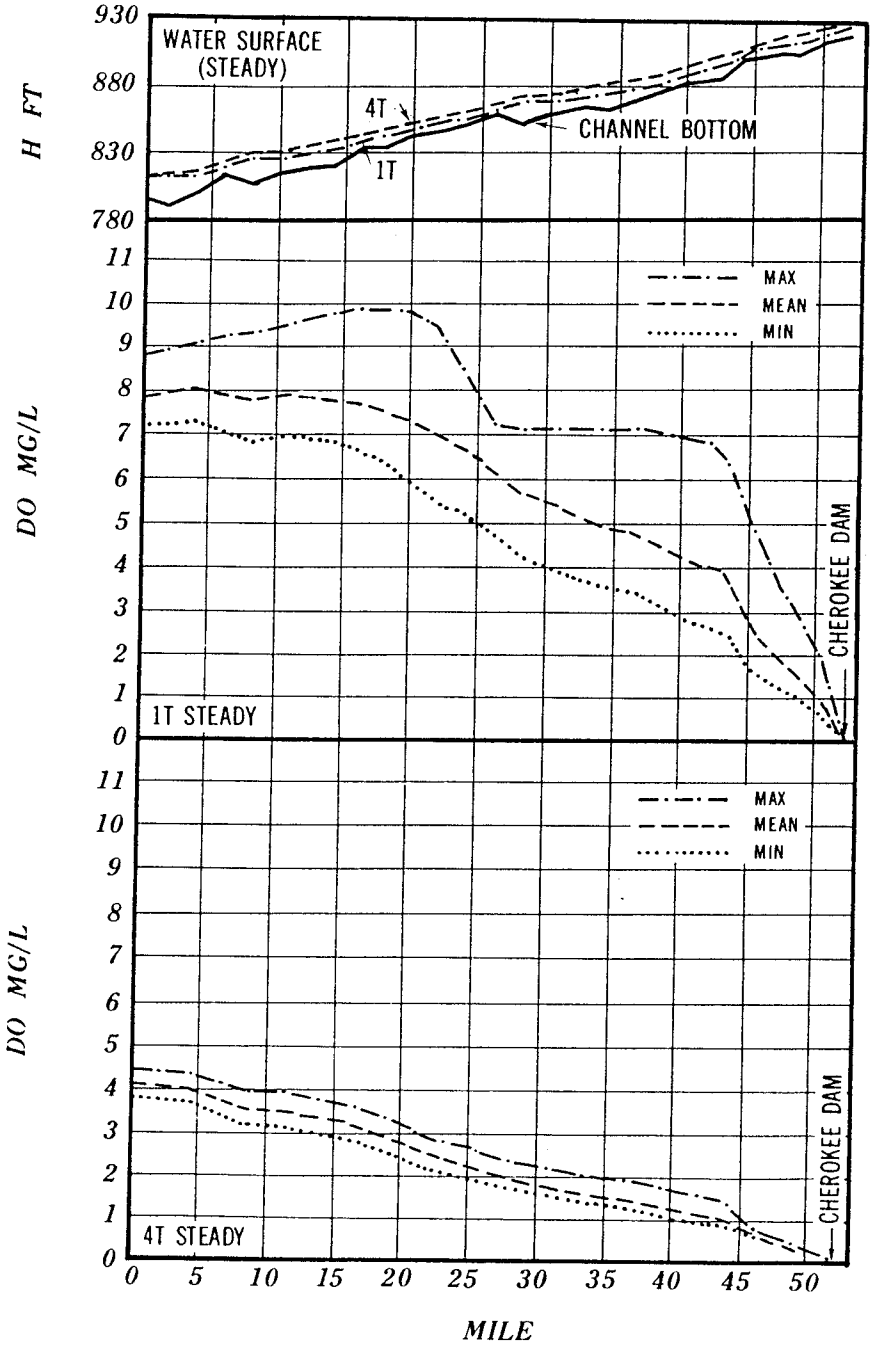


Figure C-17. Modeled Longitudinal patterns in Cherokee Tailwater for 1-unit and 4-unit steady flow conditions. The mean DO curves were determined using a flow weighted basis.

Simulations were also made of the downstream effects of artificial aeration at Cherokee Dam. Figure C-18 shows the results of simulations for release DO concentrations of 0, 3, and 5 mg/L assuming 4-unit operation from 9 am to 9 pm each day. The lines converge in the downstream direction, indicating that only a portion of the DO improvement achieved at Cherokee Dam will appear at the downstream end of the tailwater. This occurs because of the masking effect of natural reaeration. However, the reaeration rate is directly proportional to the DO deficit below saturation (about 9 mg/L). Reaeration from 0 mg/L is therefore more rapid than reaeration from 5 mg/L, and each of the lines is asymptotically approaching the 9 mg/L saturation level, so they converge in the downstream direction. In the plot of minimum daily DO (lower box), reaeration from 5 mg/L at the dam was not enough to overcome the predawn plant respiration between turbine generating periods, so the minimum DO falls slightly below 5 mg/L before recovering downstream. The general pattern of converging lines is similar to the mean DO in the upper box.

Ft. Patrick Henry Tailwater. Ft. Patrick Dam is a 2-turbine hydropower project on the South Fork Holston River with a total generating capacity of 36 MW. Each turbine normally discharges about 3,300 CFS. Ft. Patrick Henry tail water extends 38 miles (slope 2.8 ft/mile) from the dam to the headwaters of John Sevier intake pond. Tailwater conditions are characterized by available flow regime due to hydrogeneration with low flow maintenance between generating periods by pulsing 1-unit for 1 hour every third hour. These flow patterns are superimposed on a highly vegetated channel receiving cool, moderately low DO water in summertime releases and significant BOD from municipal and industrial sources entering the tailwater in a reach 4 to 8 miles downstream from the dam. A diversion weir for an industrial cooling water intake exists 3.5 miles downstream from the dam. The weir significantly dampens the pulses provided for minimum flow maintenance but has no significant effect on turbine flows lasting several hours. Industrial thermal loads just downstream from the weir elevate the river temperature 5 to 10°C at this location. The North Fork Holston River forms its confluence with the South Fork about 8 miles downstream from the dam. Large pools with fairly high SOD exist just downstream from the confluence.

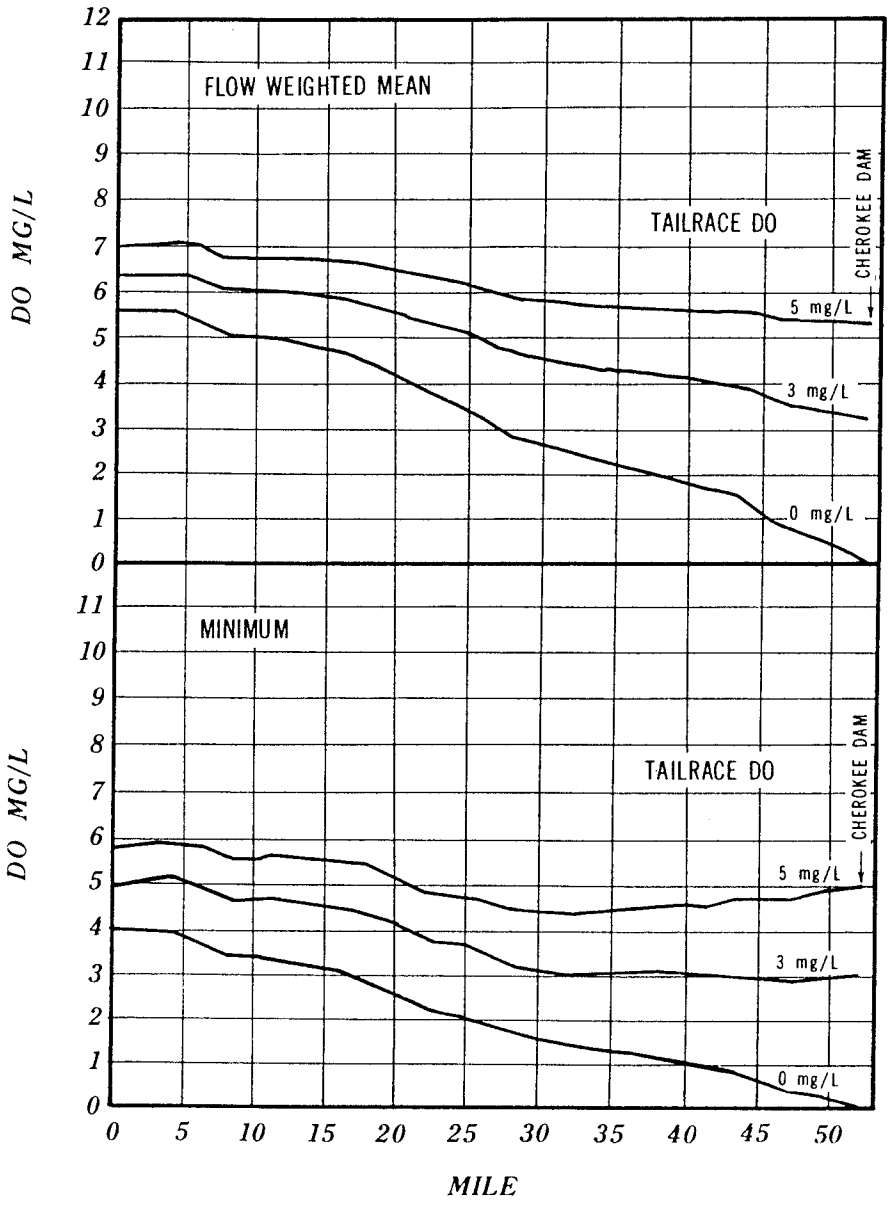


Figure C-18. Modeled Longitudinal DO patterns with artificial aeration of Cherokee releases during 4-unit operation for 12 hours (9 a.m. to 9 p.m.) each day.

A water quality survey was conducted in June 1985 to calibrate the dynamic river water quality model for the 20-mile reach below Ft. Patrick Henry Dam. During the survey period, flows averaged 1,000 to 1,200 CFS through the reach, North Fork inflow averaged 220 CFS, and release DO from Ft. Patrick Henry was just over 3 mg/L. Figure C-19 shows the channel bottom and water surface profile and measured longitudinal patterns of diurnal maximum and minimum DO concentrations during the 48-hour survey period. Reaeration is slowed in mid-reach due to the combined effects of upstream waste loads and deep pools with high SOD just below the confluence of the North and South Forks (SFHRM 0.0).

The dynamic river water quality model was used to simulate a base case of critical DO conditions assuming a simultaneous combination of extreme low flow conditions on the North and South Forks (minimum pulsing schedule) of the Holston River; low DO and high temperature releases from Ft. Patrick Henry Dam; moderately low solar radiation; and municipal and industrial waste loads at permit levels. Modeling results in the following paragraphs are described in more detail by Hauser and Ruane (Ref. C-28 and C-29).

The relative influence of major DO processes can be assessed by a series of simulations in which each DO demanding process is removed incrementally from the base case (lower line in Figure C-20) until near saturation levels were reached. These simulations were of several days duration and included diurnal variations in DO, but the results are presented as a daily average. In the base case simulation, release DO from Ft. Patrick Henry Dam was 3 mg/L. Moving downstream, the daily average DO in the base case reaerated to around 4.5 mg/L at the diversion weir. The small dip in DO at this location was due to the stagnating effect of a withdrawal (and downstream return) of nearly all the river flow for cooling water from the diversion weir pool. Saturation DO dropped sharply just below the weir due to the thermal load of the return cooling water that elevated the river temperature by about 10°C. Just downstream from the weir, several major waste loads are discharged into the river, causing the DO to begin to drop as reaeration is overtaken by the oxygen demand of the organic load. A series of pools beginning just below the confluence with the North Fork and extending for several

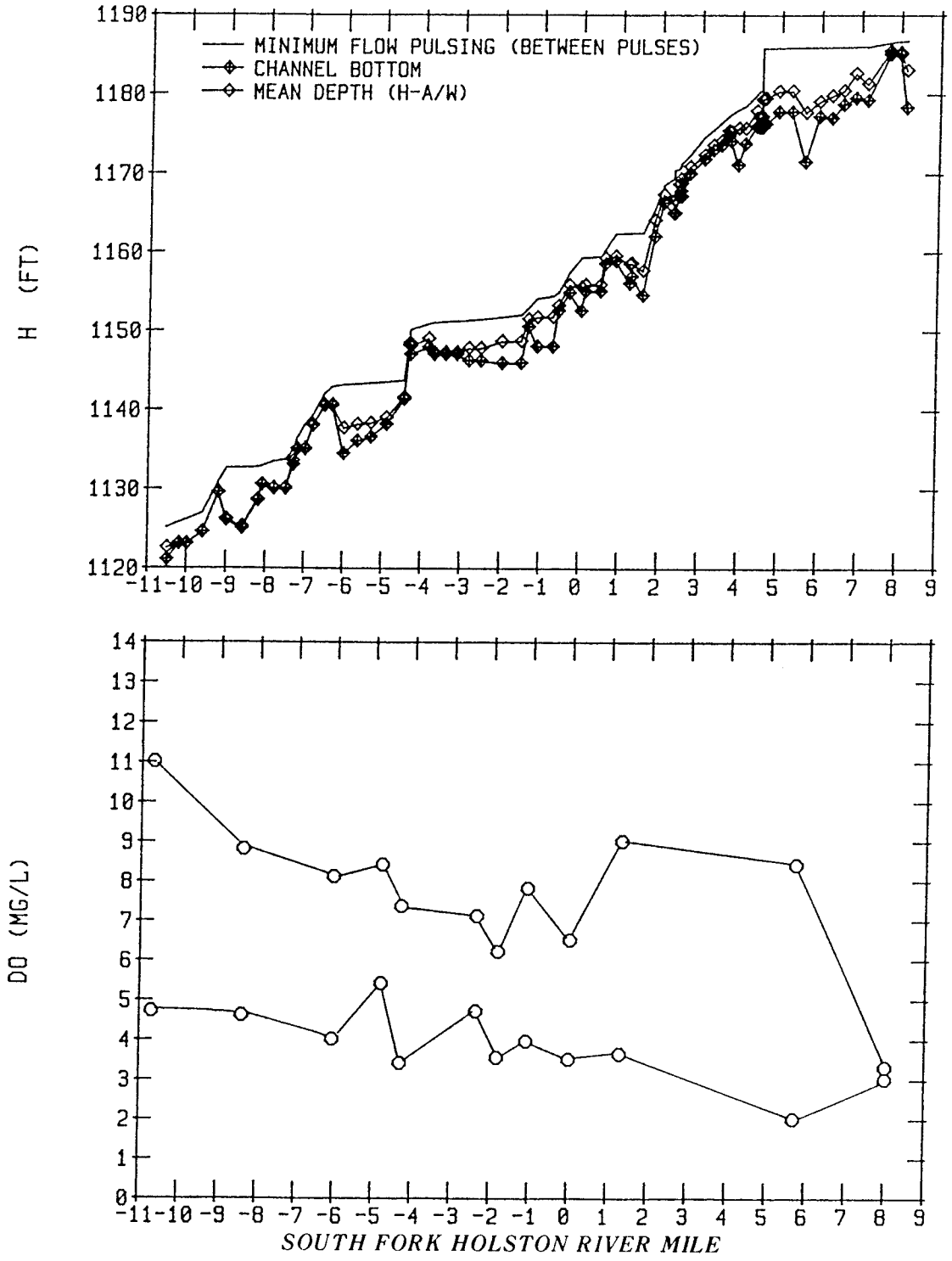
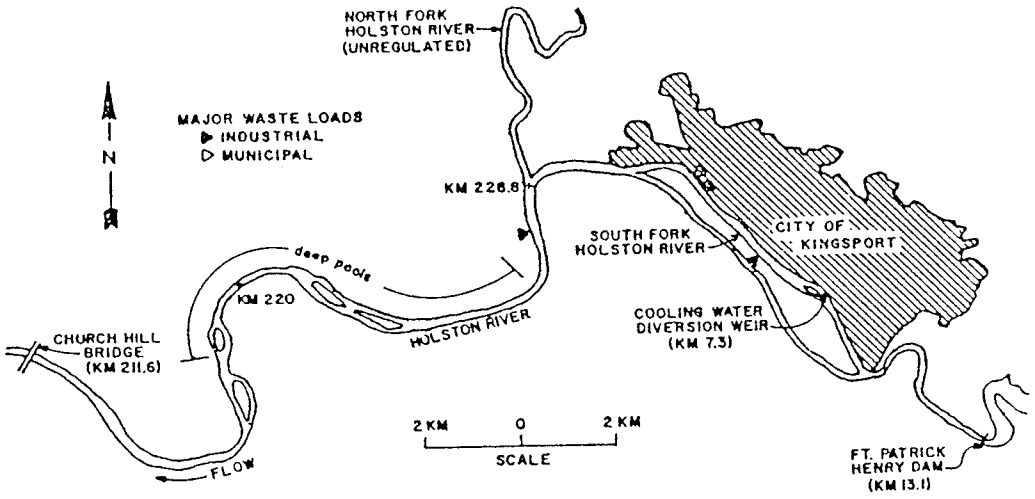


Figure C-19. Longitudinal DO patterns during June 1985 survey of Ft. Patrick Henry tailwater.



Location Map

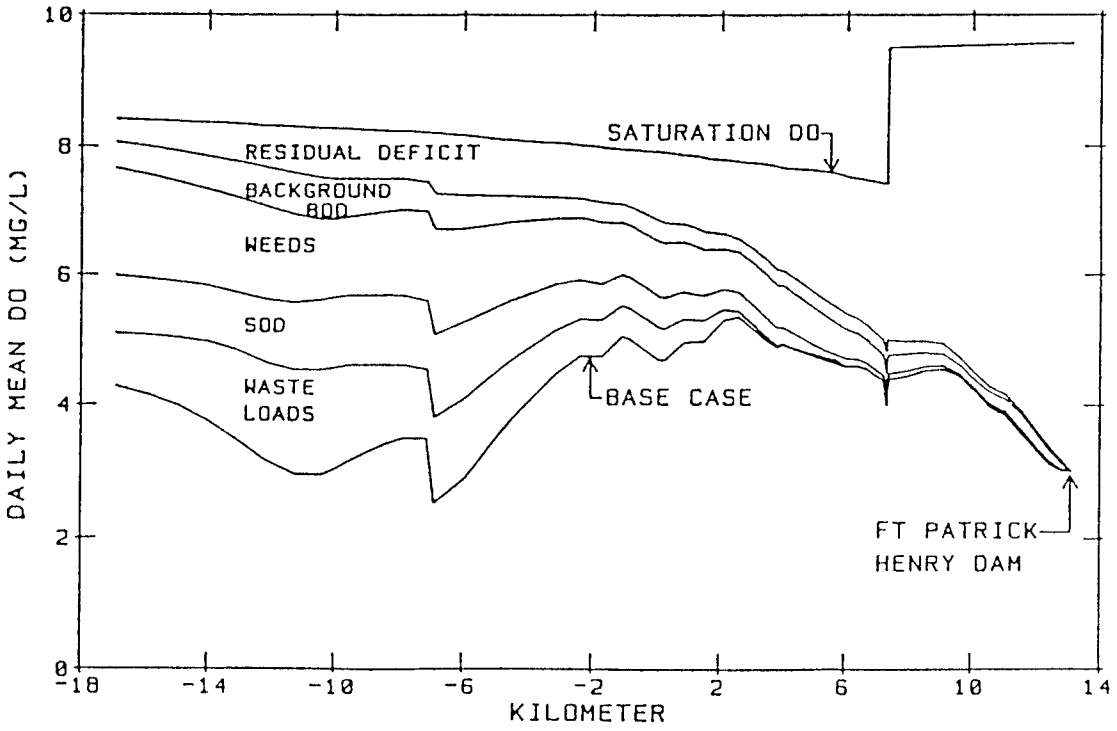


Figure C-20. Modeled relative influences of DO demands in Ft. Patrick Henry tailwater (Ref. C-30).

miles downstream contributed greatly to DO depletion due to high SOD and long residence time. The reaerating effect of a very turbulent shoals section can be seen midway along the reach below the confluence, where a 1 mg/L recovery in DO occurs across the shoals.

DO sinks were removed in the following order: waste loads, SOD, photosynthesis and respiration of macrophytes, and background BOD sources. The remaining deficit at the end of the reach after removal of the above DO demands was due to insufficient cumulative reaeration at this location to bring the large upstream deficit to saturation. Approximately 30 percent of the DO deficit at the DO sag location was due to waste loads, about 25 percent was due to weed respiration, about 20 percent was due to high SOD levels, and the remaining 25 percent was due to background BOD and residual deficit from the low release at Ft Patrick Henry Dam.

Simulations were made of the effects of various DO improvement strategies on DO near the DO sag, and the effects of each are compared to a base case in Figure C-21. The base case assumes 52 CFS daily from the North Fork; 750 CFS daily on the South Fork maintained by pulsing Fort Patrick Henry for 1 hour every 4 hours; release temperature and DO of 17°C and 3.0 mg/L, respectively, from Ft. Patrick Henry; temperature and DO from the North Fork were 27°C and 7.0 mg/L, respectively; and he temperature of 670 CFS return cooling water was 30.5°C.

Figure C-21a shows the improvement in DO from implementing simultaneous treatments at all four major waste discharges and from implementing the best single treatment. None of the individual treatments improved mean DO at the sag by over 0.4 mg/L, and simultaneous treatments improved the mean DO by about 0.9 mg/L.

Figure C-21b shows how the addition of a 1-hour pulse each day just prior to a regular pulse at 9 pm increased the daily mean DO by about 1 mg/L at the DO sag (about the same improvement as all the waste treatment improvements combined). Two and three hour pulses resulted in similar but diminishing DO improvements.

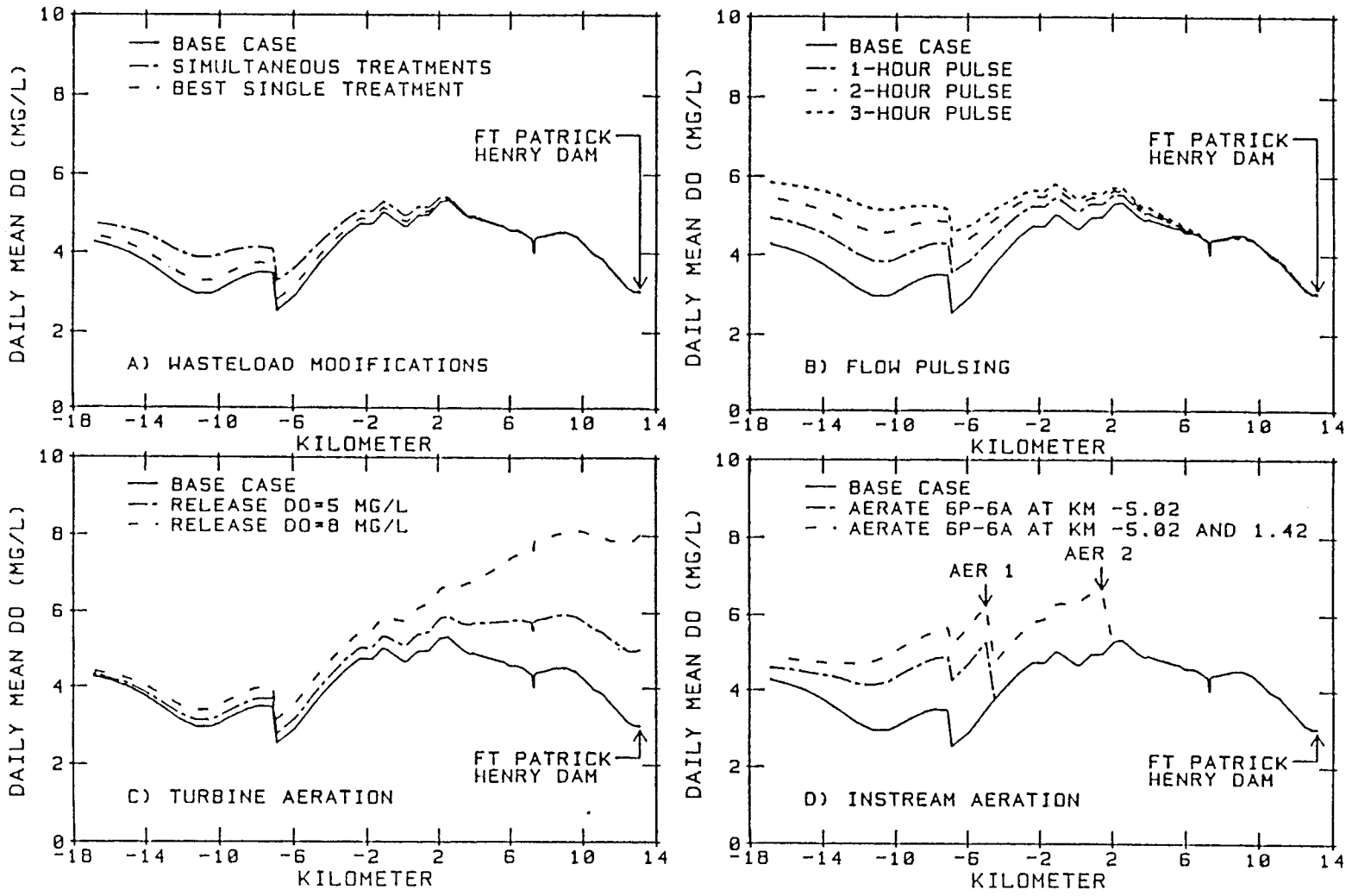


Figure C-21. Modeled effects of DO improvement strategies in Ft. Patrick Henry tailwater.

Figure C-21c shows the effect of aerating releases from the base case 3 mg/L to 5 mg/L and 8 mg/L. In each case, the DO improvement from aeration that was apparent immediately below the dam was diminished by approximately 90 percent at the DO sag location. This diminished improvement in the downstream direction is due to the more rapid natural reaeration of the DO depleted base case compared to that of the aerated case. Aerating higher flows to 5 and 8 mg/L would have resulted in a greater downstream DO improvement.

Figure C-21d shows the effect of adding oxygen at a rate of 7,260 kg/day or a 12-hour period between 6 pm and 6 am (net 3,630 kg/day) at two locations above the DO sag. Similar to aerating dam releases, DO improvement from instream aeration rapidly diminished downstream from the aeration source at such low flows.

Norris Tailwater. Norris Dam is a large 2-turbine hydropower project on the Clinch River with a total generating capacity of 100 MW. Each turbine normally discharges about 4,200 CFS. Norris tailwater extends 13 miles (slope 2.2 ft/mile) from the dam to the headwaters of Melton Hill Reservoir. Tailwater conditions are characterized by a highly variable flow regime due to hydrogeneration with low flow maintenance from a re-regulation weir. This 5 ft. re-regulation weir constructed 2 miles downstream from Norris Dam maintains a minimum 200 CFS between turbine generating periods but provides no significant re-regulation of turbine flows lasting more than about an hour. During extended periods of non-generation, 1-unit is pulsed twice a day to refill the re-regulating pool. These flow patterns are superimposed on a mildly vegetated channel receiving very cold, moderately low DO water in summertime releases and very low BOD from background or local sources.

Figure C-22 shows water surface and channel profiles with observed longitudinal patterns of temperature and DO in the first four miles of the Clinch River below Norris Dam from a field survey conducted during low flow conditions on (September 22, 1985) and during 1-unit operation (September 23, 1985). These measurements and associated modeling are described in detail by Shiao, et al. (Ref. C-30).

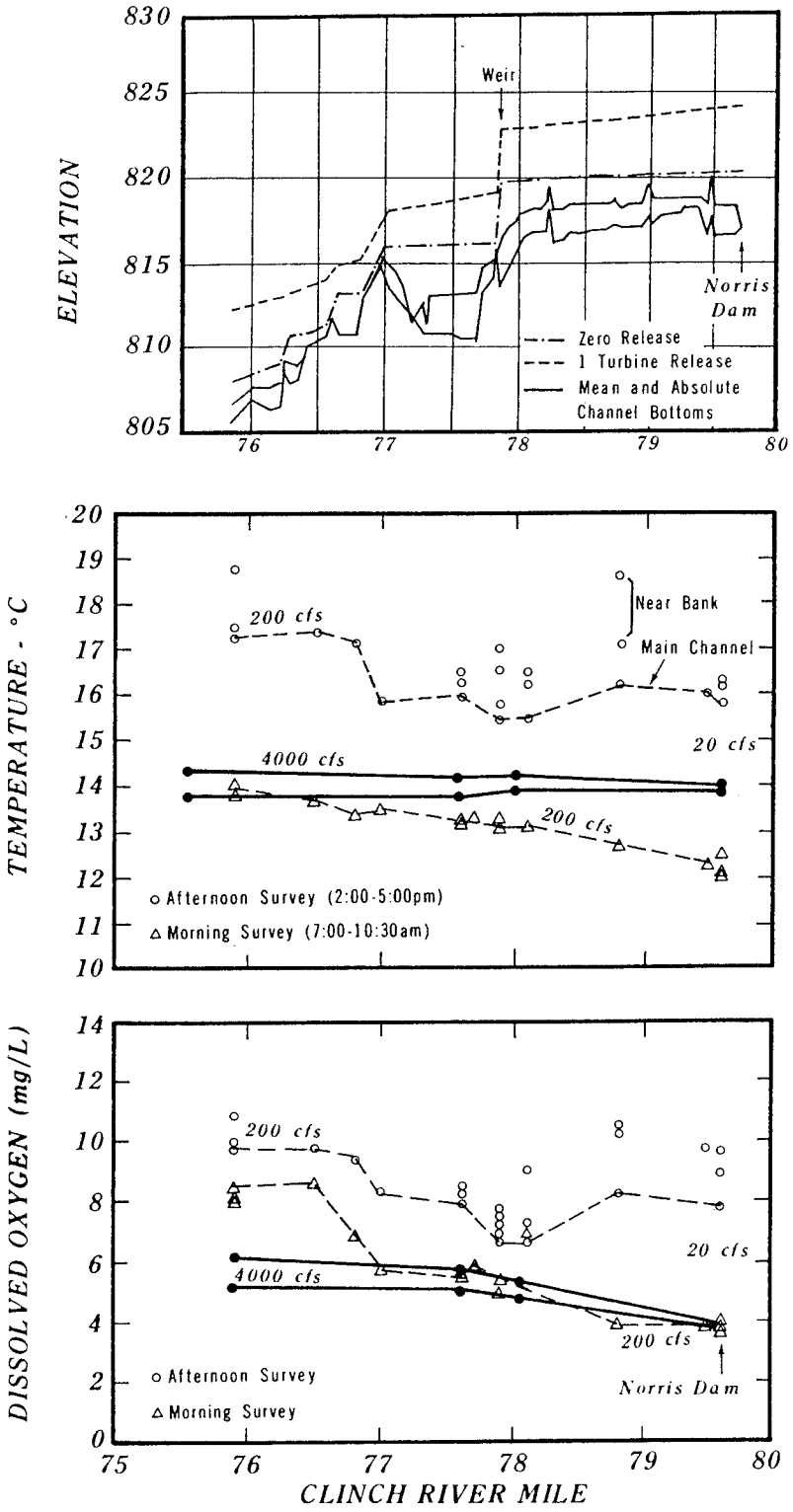


Figure C-22. Longitudinal temperature and DO patterns during September, 1985 survey of Norris tailwater.

The upper portion of the figure shows pool and riffle locations and depths that occur during low flow and 1-unit flow conditions. Also shown is the re-regulation weir in place at CRM 77.9 during the DO survey.

The lower two boxes show temperature and DO measurements. During the survey period, flows were at leakage conditions, increasing longitudinally from about 20 CFS at Norris Dam to about 200 CFS at the weir site and downstream. A dashed line connects data measured in the main channel during low flow.

Nighttime DO increased from 4 mg/L at Norris Dam to 8.5 mg/L under low flow conditions. Water travel time was measured at 9 hours during these measurements, resulting in a nighttime K_2 of 12.8 for low flow conditions. This high reaeration rate is attributable to shallow depths at such low flows and to a steep channel slope (7.8 ft/mile) downstream from the weir site. Day-night variations in DO are largest near Norris Dam where depths are shallow at low flow. The day/night variation is dampened in the deeper reaches of the weir pool and in the deep pool above Miller Island at CRM 77. Below CRM 77, the slope increases dramatically causing rapid reaeration of nighttime DO but not as rapid during the daytime because daytime DO is already near saturation.

At 1-unit flow of 4,000 CFS, depths are increased by 2 to 4 feet and travel times are shortened, so there is less opportunity for the Norris releases to reaerate in the immediate tailwater. The day/-night variation in DO (solid lines) is dampened significantly because the high flow and short residence times are overwhelming the instream processes of photosynthesis and respiration.

Appendix D

RECENT TVA FISHERIES EXPERIENCES

The Tennessee Valley Authority (TVA) operates a system of 33 dams (Figure D-1), primarily for flood control, navigation and hydroelectric production. As a result of impoundment and reservoir operation, dissolved oxygen levels are at least seasonally deficient in approximately 420 river kms (320 miles) of regulated tributary and mainstem portions of the Tennessee River system. Most dissolved oxygen deficits causing biological problems in the Valley, or not meeting state water quality standards for designated uses, occur within or below stratifying, storage-release, hydro production impoundments on the tributary rivers.

The Reservoir Releases Program (Ref. D-1) of the Tennessee Valley Authority was established in 1980 to address low DO, minimum flow and other water quality problems associated with reservoir releases that impair aqautic life or uses of releases within the Valley. An integral part of this program has been the documentation of biological changes resulting from the improvements initiated by the Reservoir Releases Improvements (RRI) Task Force.

This section summarizes TVA activities in three areas of investigation relating DO problems and fishery or macroinvertebrate alterations encountered in the Tennessee River Valley. The first is essentially a summarization of the relative seriousness of alterations to benthic communities in an extensive survey of thirteen tailwaters of the region and the relationship of these alterations to DO levels. The objective of this analysis was: to identify and correlate DO levels with benthic alterations; to identify a particular DO level that appears to dramatically affect benthic community characteristics; and to identify the most seriously affected tailwaters for which DO mitigation/minimum flow measures could be developed. Secondly, pertinent portions of an evolving field study

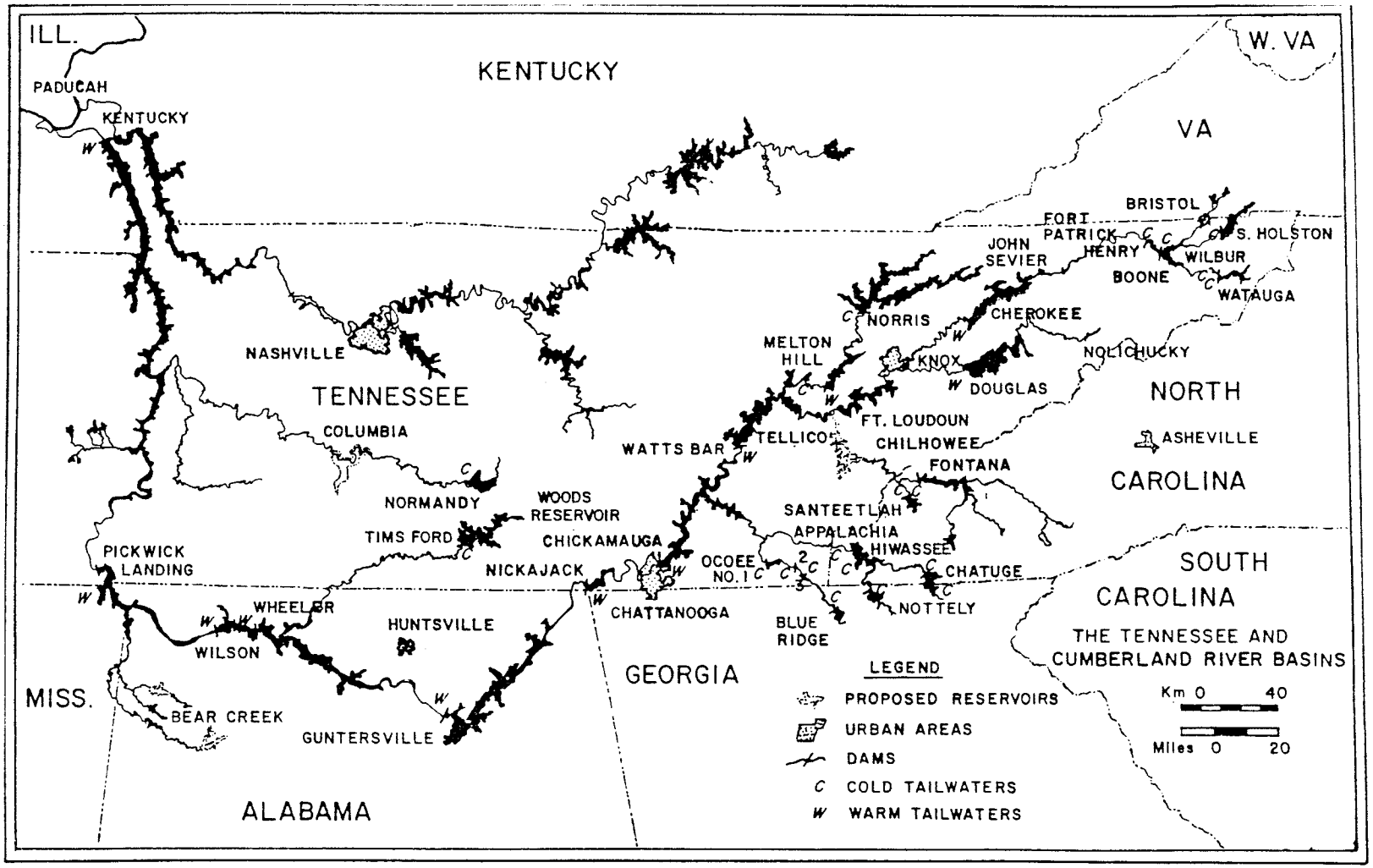


Figure D-1. Map of major reservoirs and tailwaters in the Tennessee Valley

investigating DO and minimum flow impacts on a tailwater fishery and benthic community are presented. That section represents a summarization of an intensive 1986 analysis of data (Ref. D-2) collected between 1971 and 1985 and less detailed annual reports prepared through 1988. Lastly, is a description of TVA's laboratory and "mesocosm" studies of effects of constant and fluctuating DO levels on particular fish species, which were conducted at the Aquatic Research Laboratory near Athens, Alabama.

Dissolved Oxygen Relationships To Benthic Communities On Thirteen Tributary Tailwaters Of The Tennessee River Valley

In 1972, TVA initiated a series of tailwater investigations with the objective of inventorying the aquatic biota characterizing reservoir tailwaters fauna. These data were used to evaluate the effects of changes in abiotic ecosystem components resulting from dam construction and operation on the aquatic fauna. Both biological and water quality information were collected at thirteen tailwaters (Table D-1) between 1972 and 1979. Selected water quality parameters including water temperature, turbidity, stream flow, conductivity, pH, dissolved oxygen, nitrogen, phosphorous, hardness, alkalinity, and metal concentrations were collected at most dams and compared to biological data from each tailwater. When available, metal concentrations were screened for chronic or acute levels. Biological information collected included benthic macroinvertebrate and fish samples at stations located thoughout the tailwaters. The number of stations, locations, and distances downstream from each dam varied due to differences in channel morphology, flows, substrate types and other considerations in study design, but stations were located so as to include the tailwater areas outside immediate downstream scour zones and within tailwater reaches likely to still be DO-depleted.

Although water quality and biological parameters differed in each tailwater, similarities between tailwaters were evident. Nine of the 13 tailwaters had seasonal dissolved oxygen deficts, 11 had cold water discharges, all had short-term temperature fluctuations and increased fluctuating water levels, 10 had low minimum instream flow, and all had reduced input of food resources (allochthonous material) from upstream aquatic and terrestrial sources. These factors have all been idenfied in the literature as affecting tailwater biological

Table D-1

PHYSICAL AND CHEMICAL CHARACTERISTICS OF THIRTEEN TAILWATERS INVESTIGATED IN THE TENNESSEE VALLEY FROM 1972 THROUGH 1979

	Zero Discharge Days	Minimum Flow (7Q10)	D.O. Days ((5 mg/l)	Drainage Area (k m^2)	Elevation (M)	Mean Temperature	Minimum D.O.	Reservoir Group
Cherokee	45.8	650	147	8880	283	13.7	0.0	1
South Holston	29.0	154	93	1820	454	9.2	2.0	2
Ft. Patrick Henry	0.0	446	93	4929	365	12.4	2.0	2
Apalachia	3.3	370	12	2639	257	12.9	5.0	3
Chatuge	62.2	86	103	489	550	12.3	1.0	1
Tims Ford	41.3	85	102	1370	230	10.6	0.7	1
Wilbur	45.8	119	13	1220	483	10.0	4.0	2
Nantahala	19.2	N/A	0[a]	344	612	N/A	2.0	3
Blue Ridge	27.7	157	59	601	471	13.0	4.0	2
Douglas	6.8	1060	119	11760	267	14.8	0.5	1
Norris	20.7	250	82	7540	252	11.5	0.0	1
Chilhowee	0.0	895	0	5120	246	12.2	6.0	3
Nottely	76.6	N/A	88	550	492	12.8	1.0	1

a = estimated
* = Reservoir groupings based on D.O.:
1 = one ppm or less
2 = two to 4 ppm
3 = five ppm or more

communities. It was also evident that parameters including dissolved oxygen concentrations, water temperature, and instream flow were interelated, most likely, having synergetic effects.

By looking at biological samples longitudinally from dams downstream, both diversity and biomass of the macroinvertebrate communities generally increased. This was attributed to dampening of the effects of the operation of dams including reaeration; contribution or flow, allochthonous materials and colonizing organisms from tributary streams to instream river flows; and short-term fluctuations in water levels and temperatures. This led to the rational that by pooling data from all 13 tailwaters, analyses of relationships between water quality/physical parameters and biological data, particularly faunal diversity, could identify limiting factors affecting the health of the aquatic fauna caused by dams and operational regimes.

Hill, (Ref. D-3) compared the characteristics and determinants of the fisheries resources of three of these cold tailwaters in Tennessee. He concluded that dissolved oxygen was the factor most limiting to the maintenance of the benthic faunal diversity in these tailwaters and that other biological differences between tailwaters such as standing crops, seasonal abundances of fish and bottom fauna were more directly influenced by temperature, mineral quality, flow regimes, and substrate composition. This led to the rationale that by pooling data from all 13 tailwaters, analyses of relationships between water quality/physical parameters and biological data, particularly faunal diversity, could identify limiting factors effecting the health of the aquatic fauna caused by dams and operational regimes.

The multivariate statistical procedure, Principal Components Analysis (PCA), was used to determine measures of trends in the benthic macroinvertebrate communities in these 13 tailwaters. PCA was used as an ordination technique to reduce the dimensions of a multispecies data set to a few dominant trends on components. An indication of ecological influence expressed by each component can often be obtained by examining the values of the species and the component scores of each sample, in this case each tailwater. Samples or tailwaters having high values on the same component are probably

responding to the same environmental influences. The interrelations among tailwaters were displayed in terms of a bivariate plot of each tailwater to permit visual assessment of the similarity or dissimilarity of the individual tailwaters (Figure D-2). The closer the tailwaters fall on this plot, the more similar the benthic faunal assemblages. Samples which fall into clusters can be classified into disinct groups. Tailwaters grouping as being similar in this case were on the extremes relative to both minimum DO and the number of days having DO concentrations less than 5 mg/L. This can be seen by comparing values for Trend-1 with species being tolerant of low DO being assigned negative values, while less tolerant species were assigned positive values (Table D-2).

To determine relationships of some of the more obvious environmental influences effected by dams, the two components of the benthic invertebrate communities identified by PCA were correlated in a standardized correlation matrix with minimum flow, DO days (number of days DO less than 5 mg/L), mean temperature, minimum DO, and discharge days (number of days with zero discharge) (Table D-3). Although correlations do not prove cause and effect, these analyses show a significant relationship between Trend-1 and both minimum DO and DO-days. These analyses support Hill (Ref. D-3) in showing a strong relationship between a healthy and diverse bottom fauna and DO concentrations. Actual DO concentrations required for a healthy benthic invertebrate community were interperted from a plot of the Trend-1 value for each tailwater (Table D-4) against minimum DO concentration for each tailwater (Figure D-3). This plot shows that tailwaters with positive values, excluding Chatuge, had minimum DO concentrations of 4 mg/L or greater while tailwaters having negative values, excluding Wilbur, were below 4 mg/L. Chatuge and Wilbur did not group well in these analyses. However, both had intermediate Trend-1 values with Chatuge having a better and Wilbur having a worse value than expected based on DO concentrations. In these two tailwaters the benthic fauna was apparently most effected by influences other than DO concentrations. The Chatuge tailwater was influenced by two large tributaries which significantly reduced the adverse effects of inadequate minimum flow and may have effected DO concentrations in the lower tailwater samples. Reasons for a lower than expected value for Wilbur are not known.

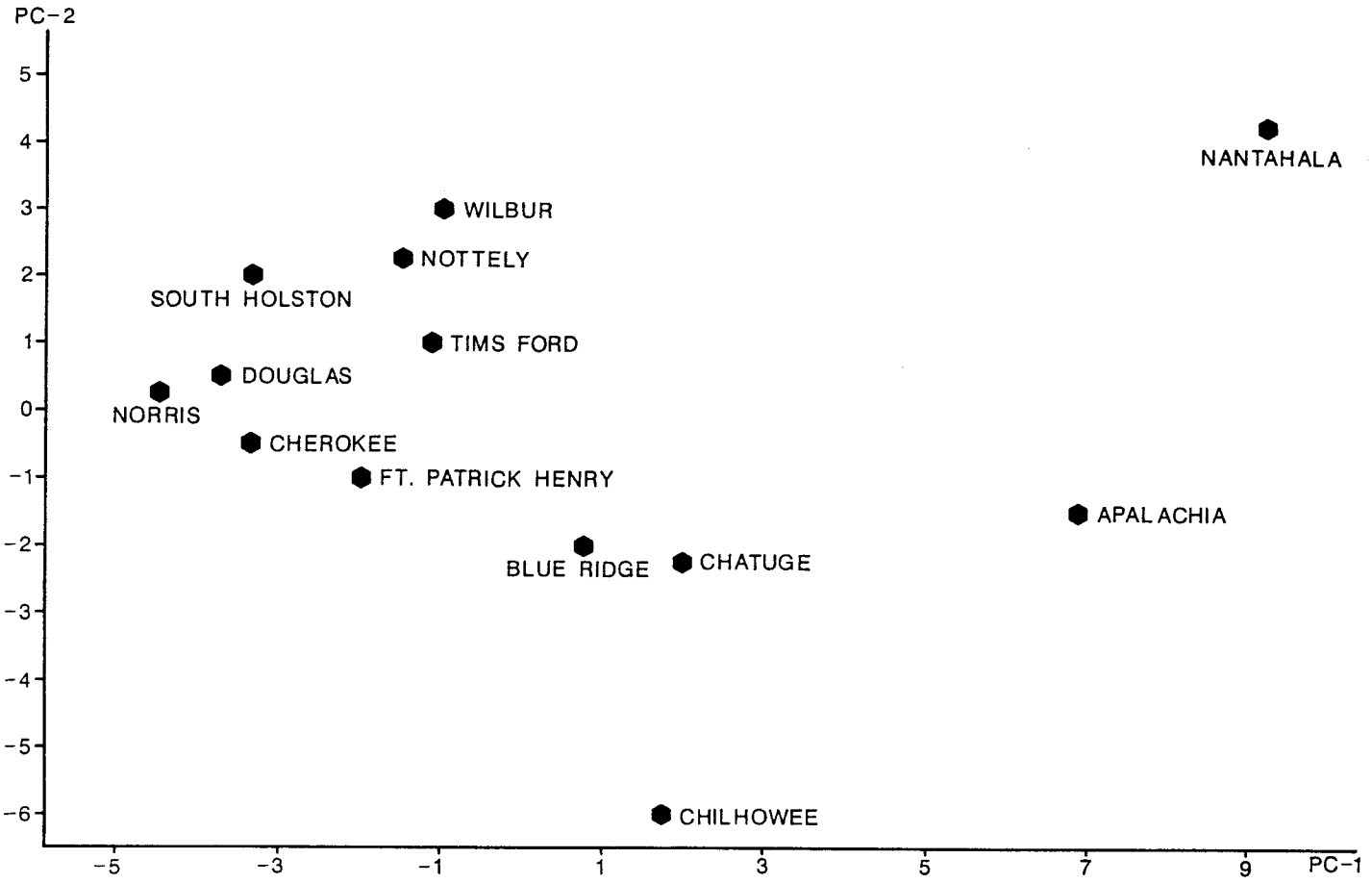


Figure D-2. Plot of PC-1 versus PC-2 for thirteen tailwaters in the Tennessee Valley.

Table D-2

PRINCIPAL COMPONENT ANALYSIS VALUES OF
MACROINVERTEBRATES FOR TWO COMPONENTS

	Trend-1	Trend-2
Nematoda	-.022343	0.262757
Hydridae	-.141293	0.191286
Planariidae	-.105366	0.160851
Oligochaeta	-.036503	0.229112
Asellus sp.	-.174965	0.091482
Lirceus sp.	-.158373	0.017748
Gammarus sp.	-.079377	-.102398
Pteronarcys sp.	0.151794	-.069342
Peltoperla sp.	0.201033	0.116759
Brachyptera sp.	0.163031	-.066290
Nemoura sp.	-.040705	0.089572
Leuctra sp.	0.148580	0.096872
Acroneuria sp.	0.185927	0.177479
Perlesta sp.	0.162893	-.093859
Isogenus sp.	0.212026	-.055296
Isoperla sp.	0.170610	0.034758
Caenis sp.	0.009607	-.193386
Ephemerella sp.	0.201286	-.113515
Baetis sp.	0.175595	0.162398
Pseudocloeon sp.	0.213165	-.036798
Isonychia sp.	0.205912	0.057034
Epeorus sp.	0.187350	0.163247
Heptagenia sp.	0.072210	-.250458
Stenonema sp.	0.213413	-.048049
Glossosoma sp.	0.182588	0.095040
Rhyacophila sp.	0.197336	0.126780
Chimarra sp.	0.162767	0.137832
Cheumatopsyche sp.	0.070381	-.162495
Hydropsyche sp.	0.179876	-.151409
Hydroptila sp.	0.040032	-.116859
Lepidostoma sp.	0.201033	0.116759
Brachycentrus sp.	0.085388	-.271902
Micrasema sp.	0.154323	-.194202
Corydalus sp.	0.168152	-.136183
Chauliodes sp.	0.153881	0.153132
Simuliidae	0.003979	-.264723
Tipulidae	0.160390	0.058475
Chironomidae	-.164552	-.044186
Atherix sp.	0.175154	0.179989
Empididae	0.038051	0.127696
Elmidae	0.154888	-.162129
Psephenus sp.	0.178881	0.067378
Parasitengona	-.044631	0.002189
Pleuroceridae	0.075689	0.159284
Physa sp.	0.000990	-.132967
Sphaeriidae	0.034904	-.258204

Table D-3

STANDARDIZED CORRELATION (R-VALUES) MATRIX OF PRINCIPAL COMPONENT AND SELECTED ECOLOGICAL INFLUENCES

	Trend-1	Trend-2
Minimum Flow	-0.1309	-0.3939
P>F	0.7013	0.2307
N=	11	11
D.O. Days *	-0.7171	0.0399
P>F	0.0058	0.8970
N=	13	13
Minimum D.O.	0.8296	-0.3708
P>F	0.0005	0.9417
N=	13	13
Temperature	0.1048	-0.3708
P>F	0.7459	0.2354
N=	12	12
Discharge Days	-0.1936	0.3450
P>F	0.5262	0.2483
N=	13	13

* D.O. day - number of days having DO concentrations less than 5 mg/L

Summary. The major useful information gleaned from this analysis is that: benthic community characteristics are significantly related to dissolved oxygen levels in a number of regulated tailwaters of the Tennessee Valley region; the relationship appears essentially linear through a range of 0 to 7 mg/L DO; improvements in benthic communities may be attainable by increasing DO levels through this range; and that a shift in benthic communities dominated by organisms tolerant of low DO conditions to a community of greater diversity with proportionaly greater dominance of organisms intolerant of low DO conditions occurs at about 4 mg/L.

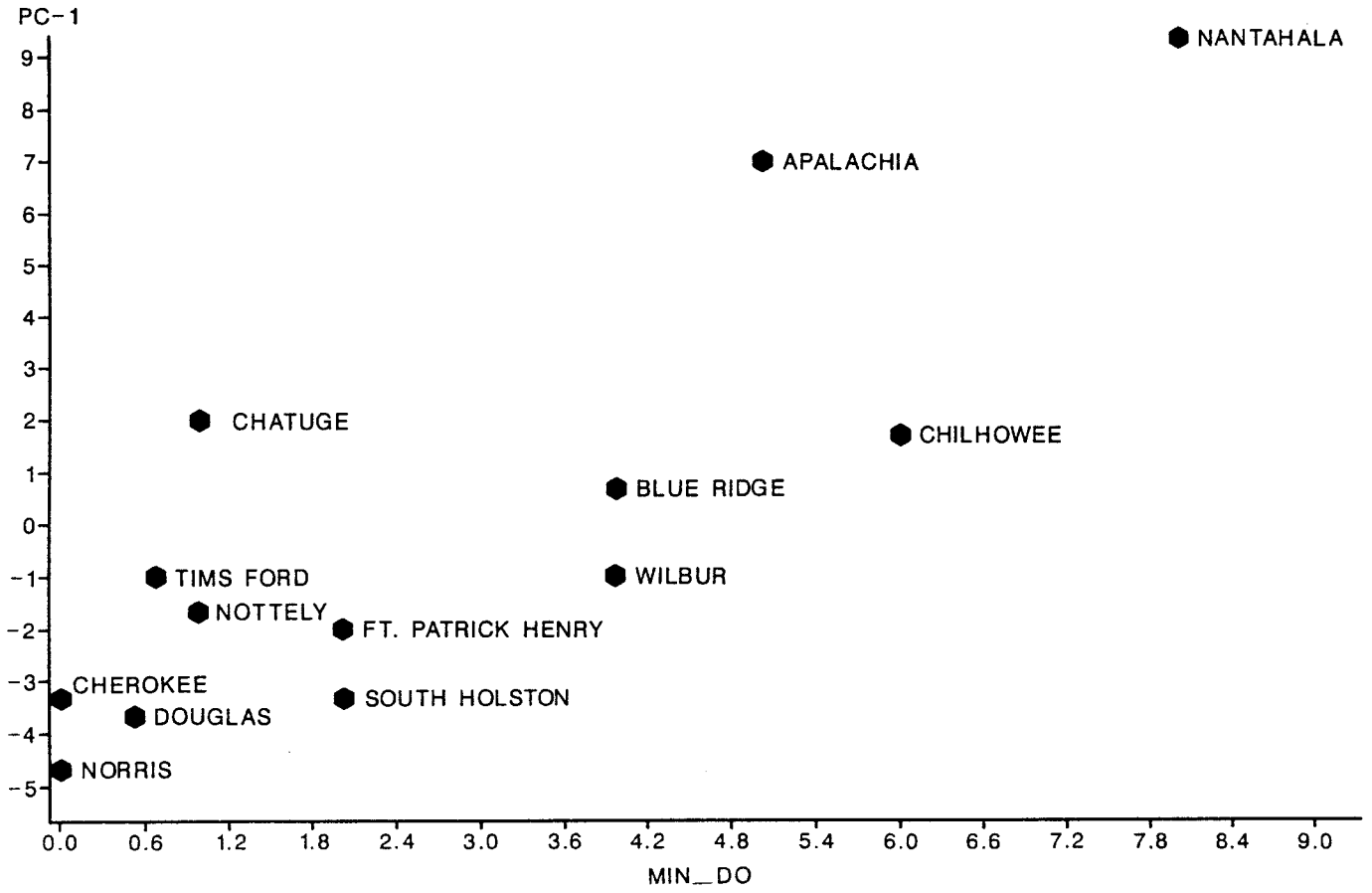


Figure D-3. Plot of PC-1 versus minimum dissolved oxgyen concentrations for thireen tailwaters in the Tennessee Valley.

Table D-4

PRINCIPAL COMPONENT VALUES AND SELECTED PHYSICAL/CHEMICAL ECOLOGICAL INFLUENCES OF THIRTEEN TAILWATERS IN THE TENNESSEE VALLEY

Tailwater	PC-1	PC-2	PC-3	Min-Flow	DO-Days	Temp	Min-DO	Disc-Day
Apalachia	6.9056	1.5142	5.0129	370	12	12.9	5.0	3.3
Blue Ridge	0.7238	-1.9880	-0.5746	157	59	13.0	4.0	27.7
Chatuge	2.0313	-2.3089	-0.6846	86	103	12.3	1.0	62.2
Cherokee	-3.4217	-0.5986	-0.8523	650	147	13.7	0.0	45.8
Chilhowee	1.7741	-5.9476	-1.6065	895	0	12.2	6.0	0.0
Douglas	-3.7364	0.6073	-0.4890	1060	119	14.8	0.5	6.8
Nantahala	9.2966	4.3302	-2.8370		0		8.0	19.2
Norris	-4.5607	0.1533	1.7300	250	82	11.5	0.0	20.7
Nottely	-1.5287	2.2431	-1.4730		88	12.8	1.0	76.6
Pat Henry	-2.0227	-1.0312	-2.3699	466	93	12.4	2.0	0.0
South Holston	-3.3261	1.9917	1.3442	154	93	9.2	2.0	29.0
Tims Ford	-1.1262	1.1186	1.6112	85	102	10.6	0.7	41.3
Wilbur	-1.0090	2.9442	1.1885	119	13	10.0	4.0	45.8

Effects Of Aeration And Minimum Flow Enhancement On The Biota And Fishery Of Norris Dam Tailwater - A Case Study

Investigations of the Norris tailwater from 1971-1977 (Ref. D-4) tentatively identified low DO and lack of adequate minimum flow as the primary factors limiting further development of the trout fishery. Partly, as a result of these findings, TVA's Reservoir Releases Improvements Program (Ref. D-1) began a demonstration effort to improve DO and flow conditions in Norris tailwater. In 1980, a hub baffle system was installed and tested intermittently on one of the two Norris turbines. This aeration system (Ref. D-5) increased minimum DO in the releases by an average of 0.7 mg/L with one unit aeration in 1981, and 2-3 mg/L from 1982-88 with two unit aeration and improved hub baffles. DO was monitored and the system operated when scrollcase DO levels fell to 4 mg/L.

Construction of a flow re-regulation weir (Ref. D-6) approximately 3.2 km (2 mi) downstream of Norris dam was completed in May 1985, and water stored behind the weir, supplied by pulsed flows from the hydropower units, has provided a minimum flow of approximately 5.7 m_3/s (200 CFS) downstream. Approximately 1/2 hour of flow from one unit is required to fill the pool behind the weir and supply flow downstream for twelve hours.

Only for a very limited number of freshwater fisheries, where data spanning several years (such as at Norris) have been collected, could population characteristics (survival, growth or harvest) reasonably be expected to produce detectable sublethal effects of low DO. The purpose of this section is to describe changes in fish, invertebrate populations and angler use in Norris tailwater that have accompanied aeration of releases and operation of the flow re-regulation weir.

Description Of The Study Area. Norris dam impounds a storage reservoir located at mile 79.8 of the Clinch River. It was impounded in 1936, covers 13,841 ha (34,200 ac) at normal full pool level, and has a drainage area of 7,539 km^2 (2,912 mi^2). Water is normally released from the reservoir's hypolimnion through two hydroelectric units. Maximum two-unit discharge is approximately 241 m^3/sec (8500 CFS).

Flow is controlled primarily for peak power generation to meet power load demands.

DO varies seasonally in the releases from Norris dam, with lowest concentrations (as low as 0.6 mg/L) usually recorded in the early autumn. Typical annual DO, temperature and discharge cycles are shown in Figure D-4.

The tailwater extends approximately 22.5 km (14 mi) downstream from Norris dam to the headwaters of Melton Hill reservoir. Average width of the river at two-unit flow is approximately 131.6 m (432 ft), while under minimum flow conditions with the weir, width is 94.5 m (310 ft).

Water level in the river fluctuates about 1.8 m (6 ft) between periods of two turbine generation and no generation. Average unregulated flow at the dam site, calculated from annual discharge measurements (1903-1969), was 120.8 m^3/sec (4,624 CFS). Stream gradient is about 0.6 m (2 ft) per mile with a normal sequence of pools and riffles. Bedrock is the primary substrate in the tailwater, with small patches of rubble, gravel and coble. Extensive growth of filamentous green algae, primarily Oedogonium with small pockets of Cladophora, covers much of the bottom.

The river is used for boat, bank and wade fishing. Most bank and wade fishing takes place when the turbines are off and access is limited to the upper 6.4 km (4 mi) below Norris dam and a section about 22.5 km (14 mi) downstream near the headwaters of Melton Hill reservoir. Most boat fishing takes place when the turbines are operating. At full two-turbine flows the entire tailwater may be floated.

Methods.

Benthos. Four quantitative samples for benthic invertebrates were collected three times per year at each of 5 tailwater stations (Figure D-5) with an unmodified 0.09 m^2 (1 ft^2) surber sampler with a 750 micron mesh net. Samples were collected from shoal areas less than 0.3 m deep from substrate consisting mostly of coble and/or rubble. Samples were fixed in 10 percent

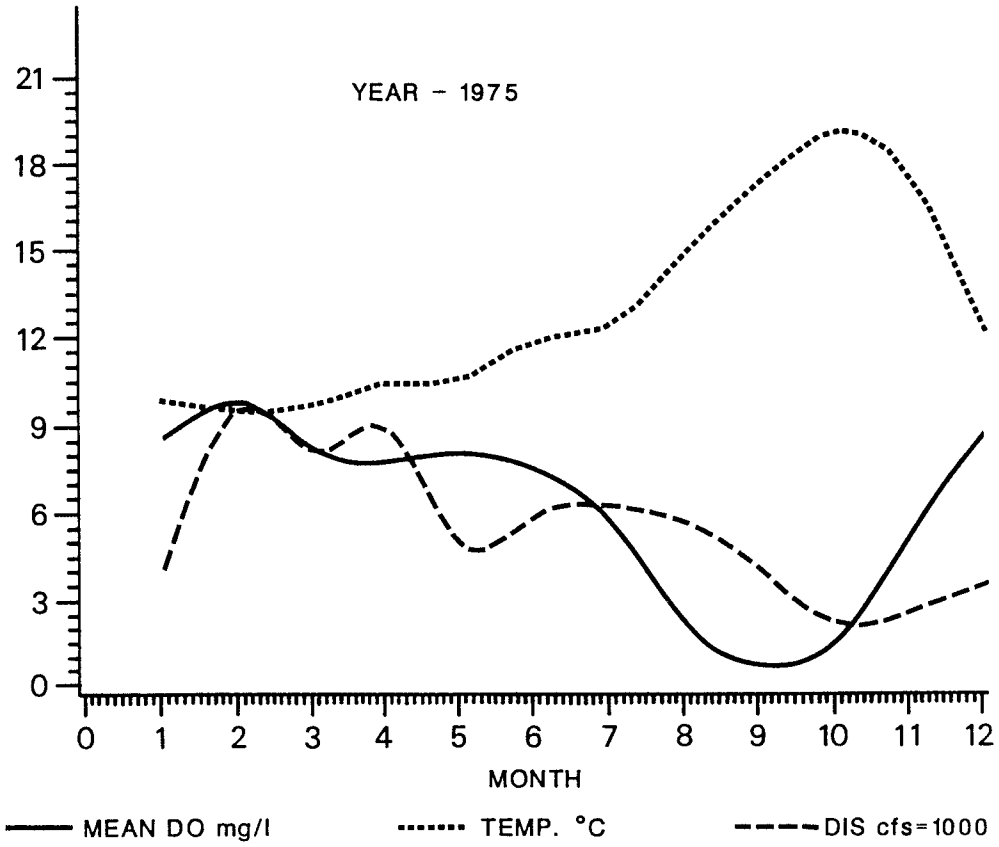


Figure D-4. Representative Historical DO, temperature, and discharge trends in turbine discharge from Norris Reservoir for 1975.

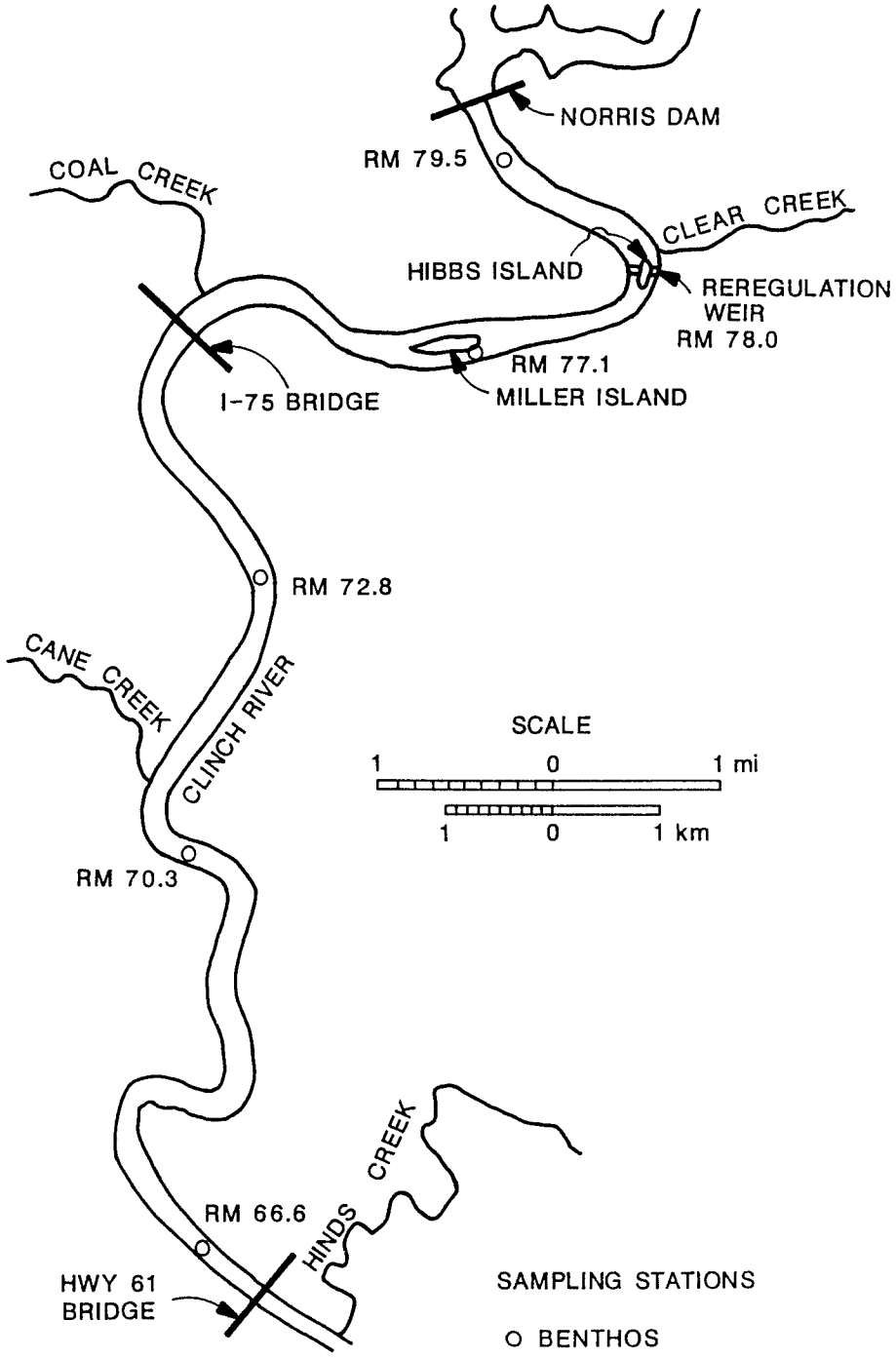


Figure D-5. Sampling stations for Benthos.

formalin solution. After sorting, invertebrates were preserved in alcohol, identified (usually to genus), and counted. From 1971-1985 entire samples were enumerated; from 1986-1987 only selected taxa (mayflies, stoneflies, crayfish, caddisflies and snails) were enumerated for reporting.

Creel Census. A roving creel census based on a non-uniform probability design developed by Dr. Don Hayne at North Carolina State University was used to characterize the fishery in the Norris Tailwater. Sampling was conducted in accessible areas of the tailwater five days a week from 1971 to 1977 and 1980 to 1988. All weekend days and holidays were included, then enough weekdays were randomly selected to complete the needed number of workdays during a period. Census days were divided into two work periods, sunrise until noon, and noon until sunset. The period censused for each day was chosen by random selection. The time for a count of anglers was then also chosen by random selection. At this pre-selected time, the clerk counted all persons fishing in accessible areas. During the remainder of the day, the clerk interviewed anglers. Information collected included time fished, number caught, and length and weight of individual fish.

The fishing pressure count was then expanded to estimate total fishing pressure for the day. Harvest estimates were made for each period as the product of the mean daily effort and estimated mean catch per effort. Estimates from individual periods were then summed to produce monthly, quarterly and annual estimates.

Trout Condition And Growth. Relative condition, proposed by LeCren (Ref. D-7) to eliminate trends in condition associated with length, was used as a measure of the changes in plumpness (condition) of fish harvested by anglers. Condition of fin-clipped, spring-stocked fingerling trout was used to examine changes in growth rates after aeration of releases and increased minimum flow. Techniques including correlation, analyses of covariance and stepwise multiple regression were used (Ref. D-2)

for analyses of data to search for spatial and temporal differences.

Results And Discussion.

Physical Changes. Aeration and flow enhancement measurably improved physical habitat in Norris tailwater. The minimum DO concentrations in the releases which typically occur during August through October were elevated by as much as 3 mg/L immediately below the dam and the effects diminished downstream (Figure D-6). Flow, temperature and water quality modeling (Ref. D-8) was conducted for low flow conditions (pulsing to maintain weir pool during a 24-hour period) typical of weekend operations. Modeling results indicate that, as compared to pre-weir years, the increased minimum flow: decreased daily maximum temperature by 0.5-1.0 °C; increased daily minimum DO by about 1 mg/L below the weir; and decreased daily maximum DO by about 2 mg/L below the weir. Under high flow (two turbine continuous discharge) water residence times are considerably reduced, dampening diurnal variations in DO and temperature. Flow model simulations under sustained minimum flow conditions (200 CFS) also indicated the wetted area of the stream increased about 25 percent as a result of impoundment upstream of the weir and about 10 percent downstream.

Modeling of historical (pre-aeration 1976-1981) and aeration (1982-1987) data (Ref. D-9) indicates that DO concentrations in Norris tailwater since 1982 have, with the exception of annually removing the hub baffles about two weeks too early (based on hindsight gained from recent analyses), been maintained consistently at 2-3 mg/L above incoming scrollcase DO levels through the low DO period (Figure D-7).

Effects On Benthic Fauna. Although the benthic fauna of Norris tailwater continues to be dominated by chironomids, isopods and amphipods (taxa typically tolerant of stressed DO conditions), less tolerant organisms are occurring more frequently (Figure D-8) and are increasing in numerical abundance (Figure D-9 and Table D-5). Caddisflies, crayfish, snails, stoneflies and mayflies, all desirable trout food organisms, now occur more

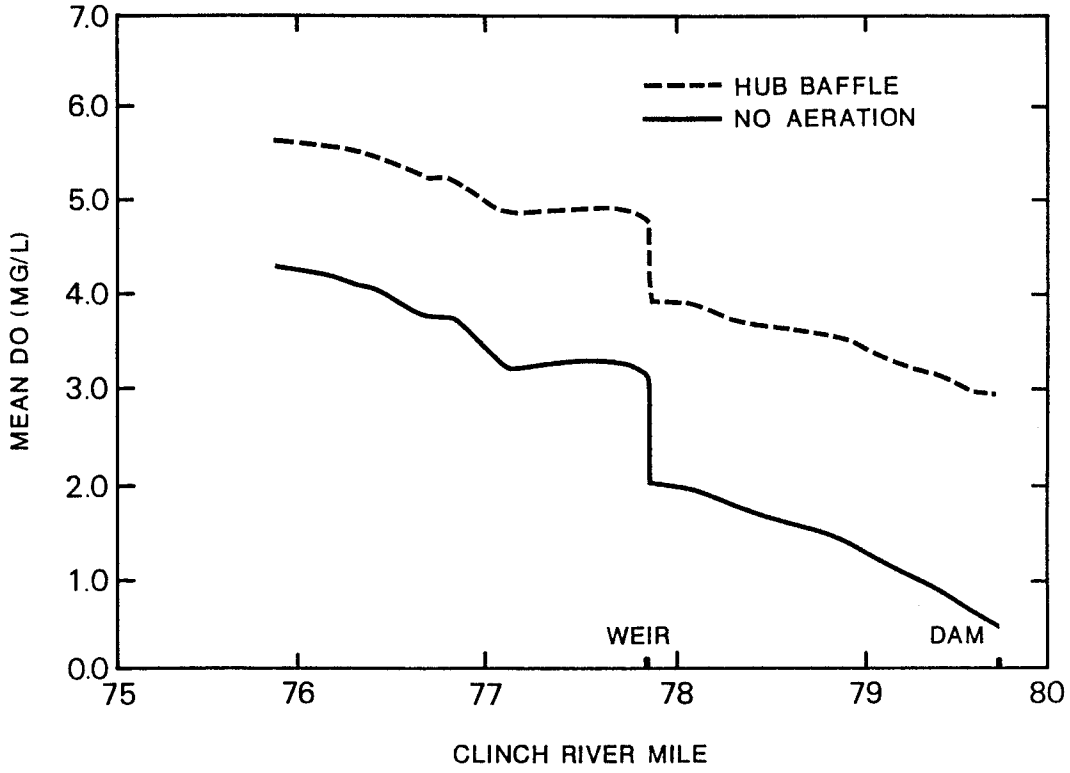


Figure D-6. Mean DO (mg/L) during a "typical" 24-hour period with 2-unit discharge (8,000 cfs) from 10 a.m. until 10 p.m. with and without Hub Baffles (Ref. D-8)

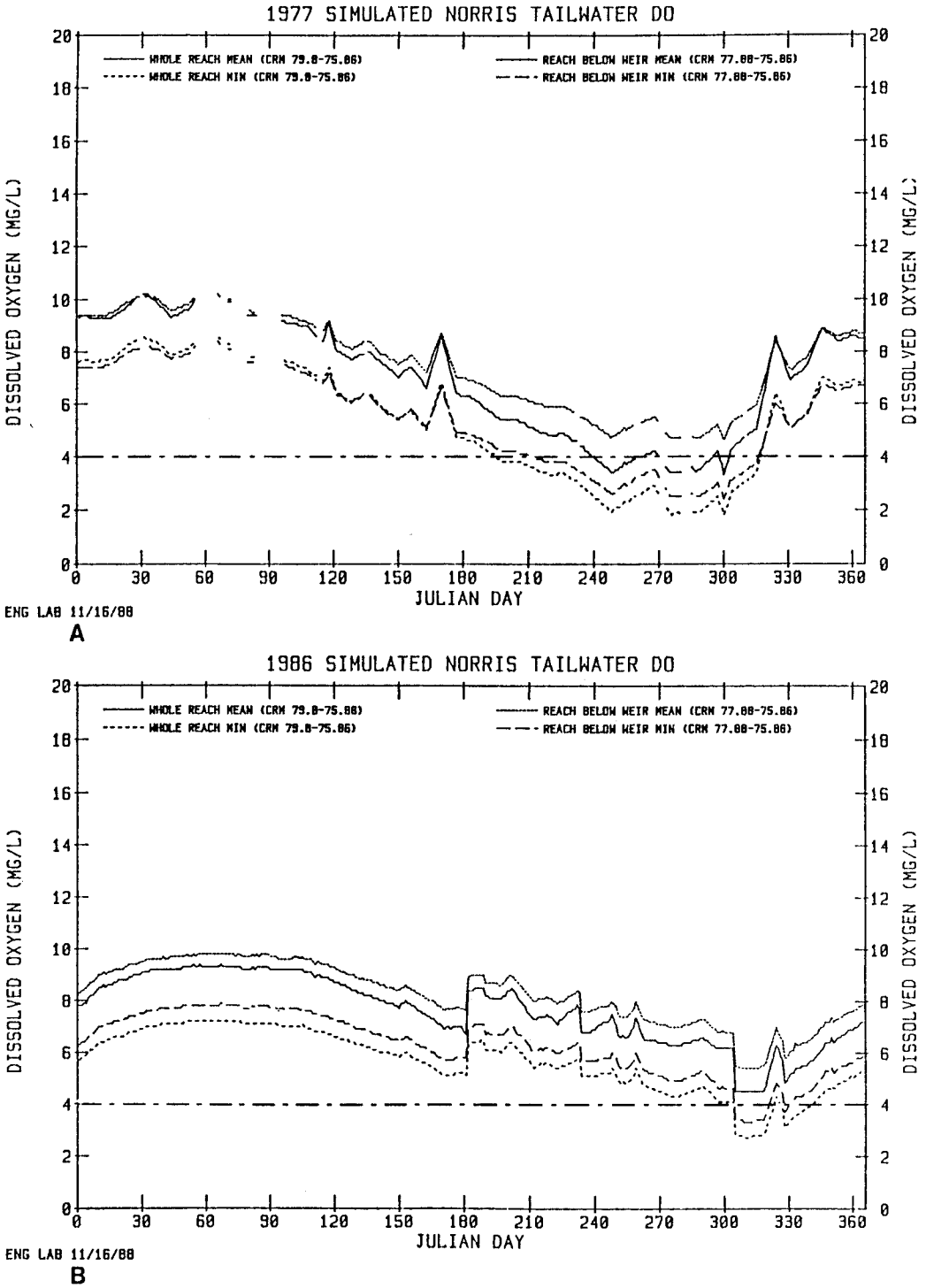


Figure D-7. Representative historical (1977) and improved (1986) mean and minima of dissolved oxygen concentrations for the entire tailwater and the below-weir reach (Ref. D-9)

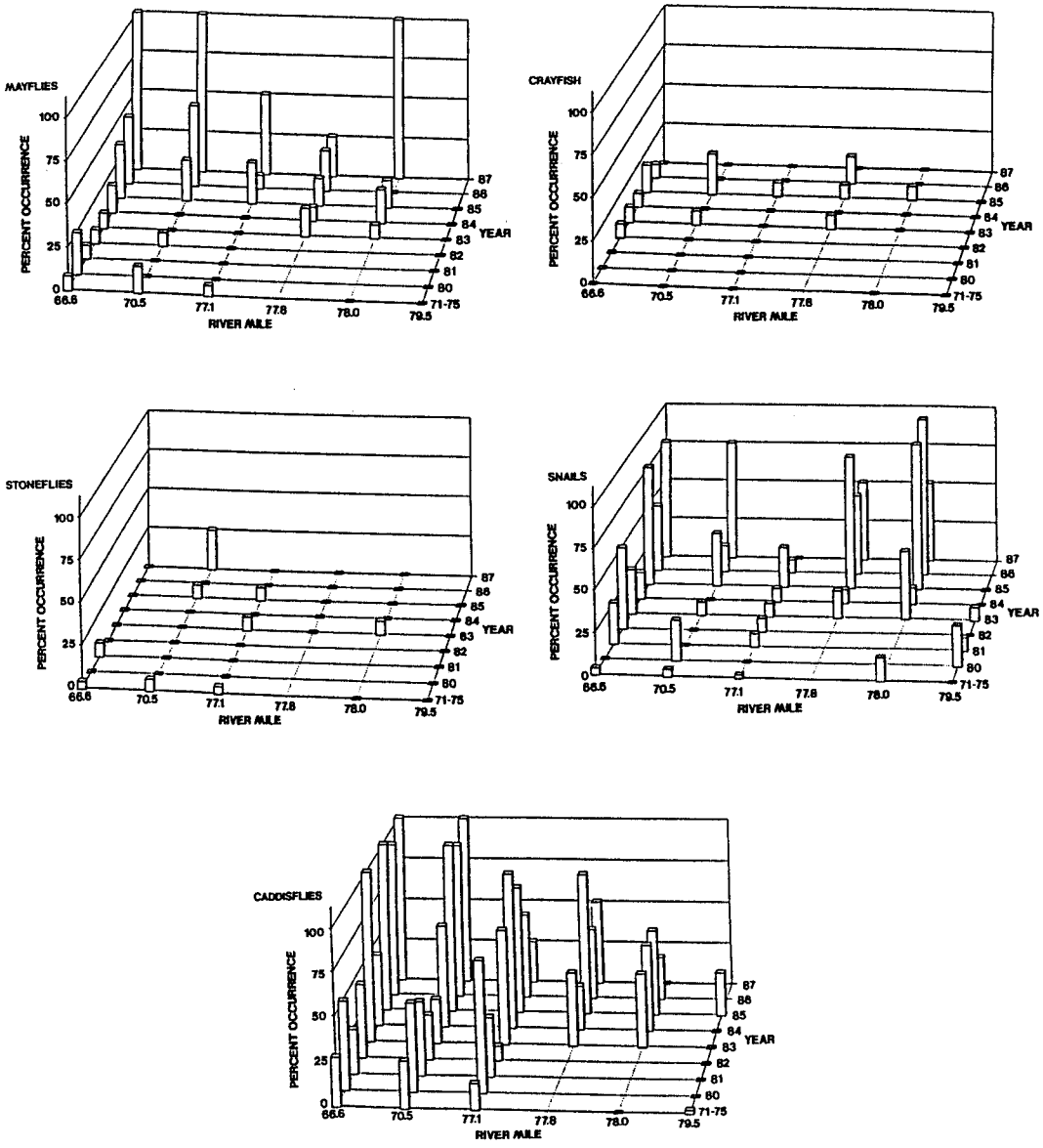


Figure D-8. Frequency of occurrence (percentage of samples which contained one or more individuals of a particular order) of selected orders of Norris tailwater bottom fauna organisms. Graphic scales are for relative comparisons within an order and are not comparable among orders. River mile 78.0 (above weir) was not sampled in the interval 1976-1982, and river mile 77.8 (below the weir) was not sampled prior to 1983.

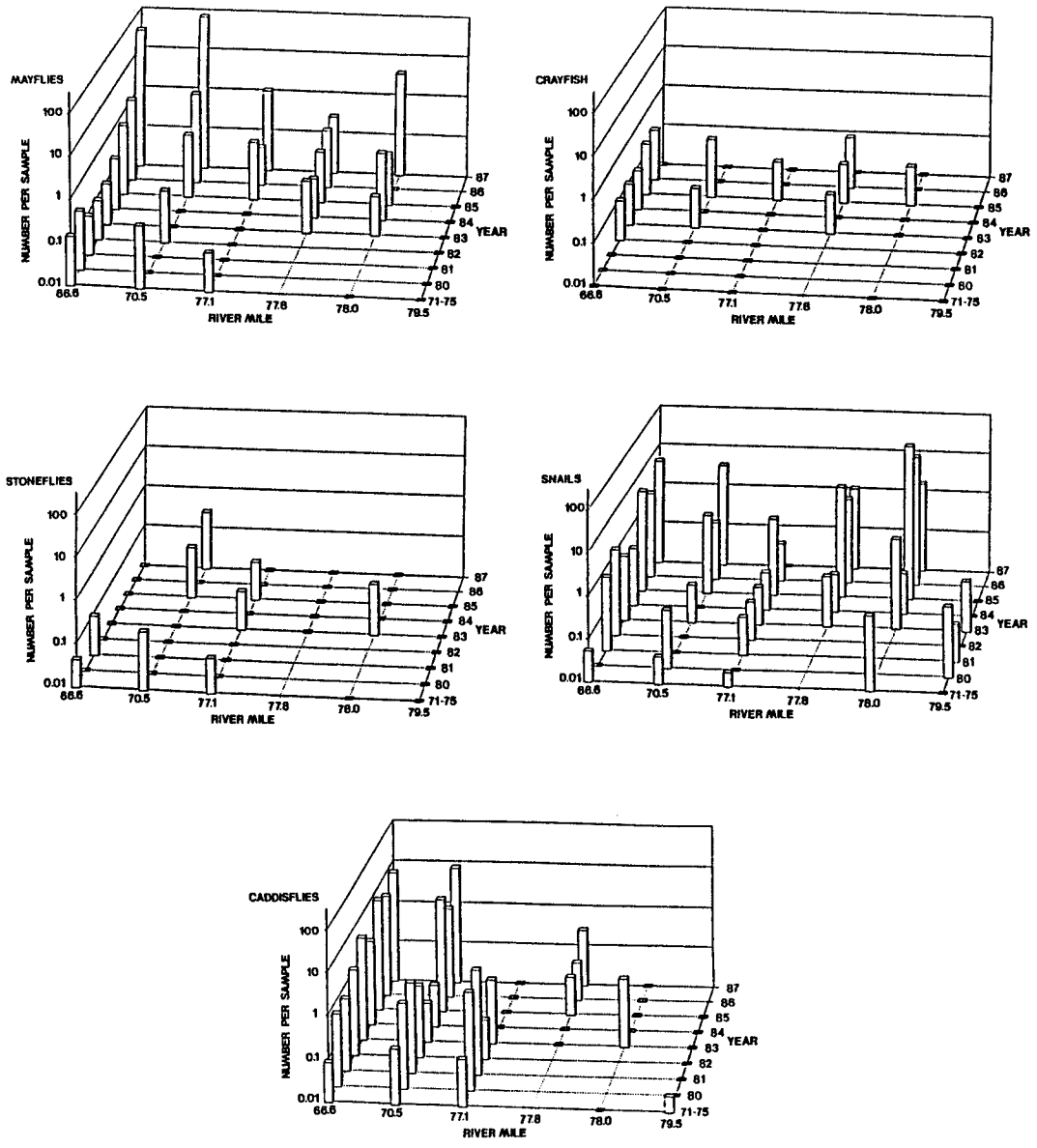


Figure D-9. Number of organisms per sample for selected benthic fauna taxa in Norris tailwater. River mile 78.0 (above the weir) was not sampled in the interval 1976-1982, and river mile 77.8 (below the weir) was not sampled prior to 1983.

Table D-5

PERCENT COMPOSITION OF 10 TAXA OF BOTTOM FAUNA ORGANISMS IN NORRIS TAILWATER FROM 1971 - 1985

Taxonomic Group	Community Percent Composition 1971-1975	1980-1984	1985
Caddisflies	0.27	1.07	3.43
Mayflies	0.01	0.01	0.01
Stoneflies	0.01	0.01	0.01
Black flies	9.11	3.98	6.54
Midges	59.98	70.74	59.99
Crayfish	0.00	0.03	0.04
Snails	0.05	0.12	0.43
Amphipods	5.76	6.13	11.13
Isopods	17.60	9.26	12.60
Others	7.21	8.65	5.72

frequently at all stations in the tailwater except immediately below the dam. The increases in these selected taxa (Figure D-8) are most prevalent for the most downstream tailwater stations. Caddisflies, crayfish and snails are also beginning to influence the benthic faunal community structure as their percentage composition increases relative to other taxa (Table D-5).

The delayed, only partial recovery of the benthic community in Norris tailwater may be because DO is still too low to allow survival and reproduction of more sensitive benthis species, a shortage of colonizers, or because recovery simply takes longer than expected.

Growth Of Trout. Growth of trout is probably the life history measurement most sensitive to environmental changes. The importance of growth estimates in field population studies lies in the effects of growth depression on potential yield or harvest. Fish growth is the overall result of a complex number of factors including water quality, temperature and dissolved oxygen; size

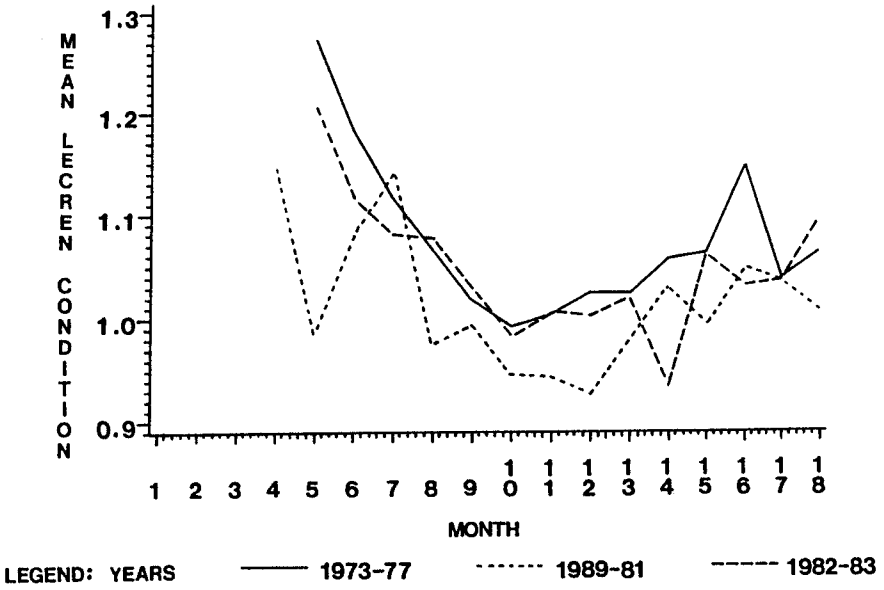
and availability of food organisms; size and age of the fish; and the number of fish competing for the same resources. Fish growth integrates all these factors and sequestering effects of one factor such as DO is extremely difficult.

Lecren Relative Condition. LeCren relative condition (Ref. D-7) is an index of fish robustness or "health" that uses length-weight information, corrected for natural trends in condition caused by differences in fish size, reproductive state or season. At Norris tailwater, except for 1985-1987, the annual patterns of monthly relative condition of trout (Figure D-10 and Figure D-11) calculated from creel data, were similar for all periods and years. Upon recruitment to harvestable size, trout from each period displayed a relatively high condition sometime between April and July, followed by a precipitous decline to a low during the low DO period about October to November. This low was followed by an improvement of condition beginning in November and December that followed fall turnover of Norris reservoir. The decline and recovery of LeCren condition strongly coincided with the annual cycle of DO levels in discharges made to the tailwater (compare Figures D-4 and D-10). Major dam-controlled physical factors (e.g., discharges, temperature and dissolved oxygen level) for the month in which fish were harvested, the previous month and an average of the two months were analyzed using correlation and stepwise multiple regression techniques (Ref. D-2). Average monthly DO concentrations below Norris (Figure D-12) was the only factor significantly related (P.F .0001) to LeCren condition of trout.

Though it may have improved growth slightly (see length-weight section), the 2-3 mg/L level of improvement in DO during 1982-1984 was not sufficient by itself to dramatically alter the overall annual cycle in LeCren condition exhibited by trout below Norris dam. At best, concentrations of DO were still within the range of levels likely to produce at least moderate (4 to 6 mg/L DO) impairments to fish growth (Ref. D-10).

Comparable data sets of seasonal condition factor on fingerling groups (cohorts) of trout from other tailwaters or streams in

A.



B.

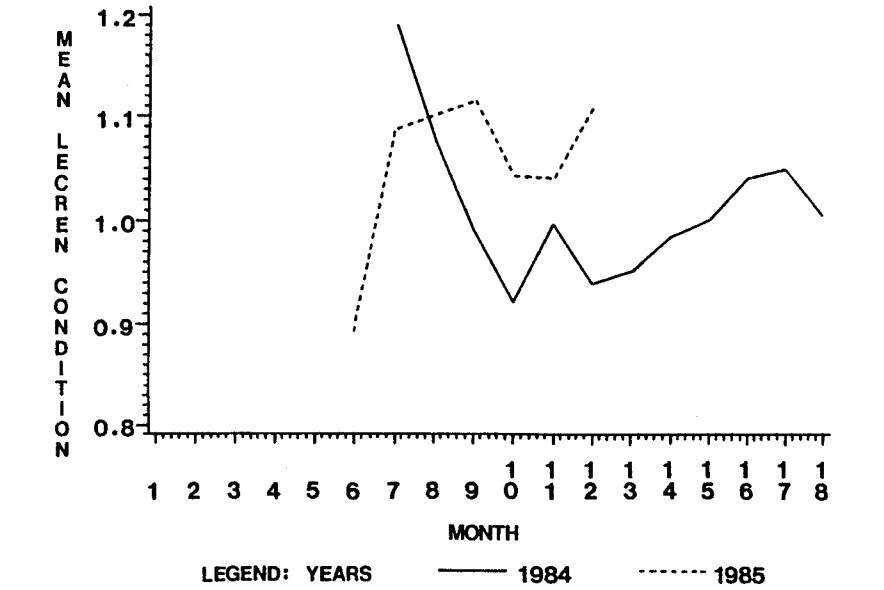


Figure D-10. Annual cycle by period of LeCren Condition Kn, for creeled rainbow trout from Norris tailwater (A) 1973-77, 1980-81, 1982-83 (B) 1984 and 1985.

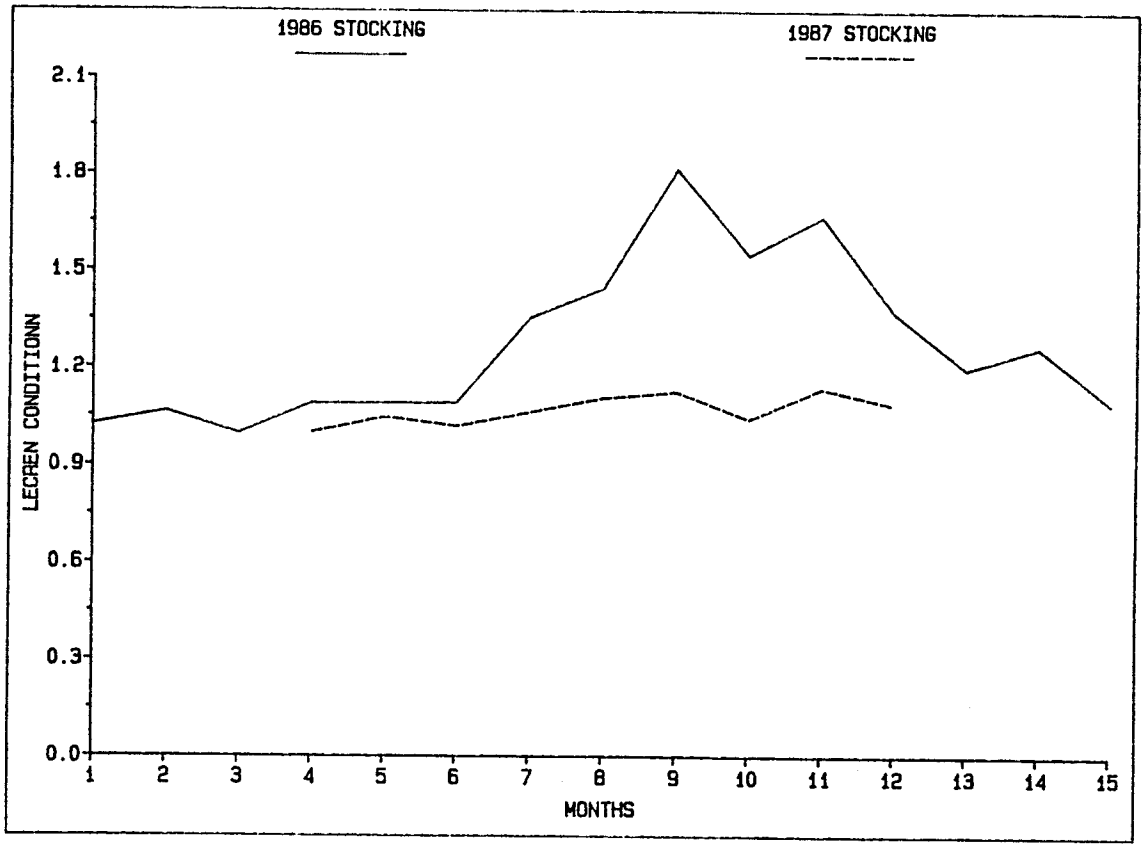


Figure D-11. LeCren Condition Kn for creeled rainbow trout from Norris tailwater, 1986 and 1987.

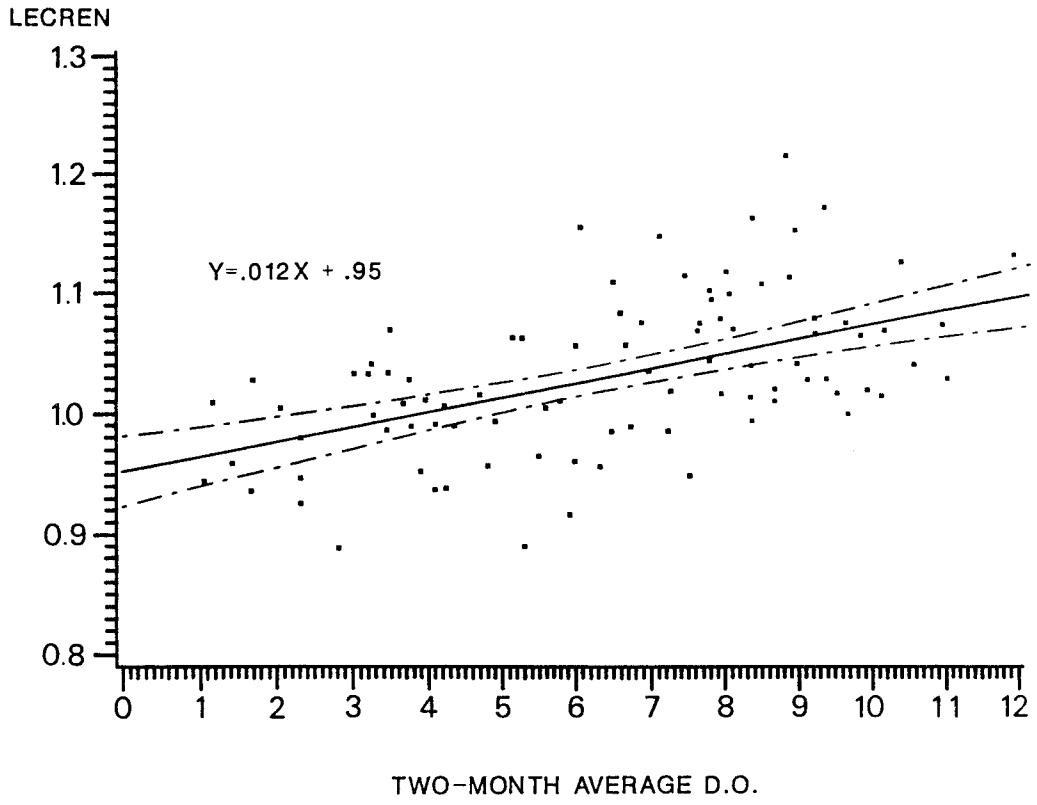


Figure D-12. Regression of LeCren Condition Factor on average dissolved oxygen (P(.0001).

the eastern United States are meagre. Much data is essentially "point" or "grab" samples with no continuous annual sampling, or is for tailwater fisheries driven entirely by stocking of catchable-sized trout. However, very limited rainbow trout data (Ref. D-11) from the tailwater below Dale Hollow reservoir, a physico-chemically similar though smaller tailwater, on the Obey River in Middle Tennessee indicated no similar pattern of decline in summer or autumn condition of trout. Three years of creel data analyzed by TVA on fingerling spring stocks of rainbow trout in the Hiwassee River (Appalachia tailwater, courtesy of Anders Myhr, Tennessee Wildlife Resources Agency), where DO levels did not fall below 6 mg/L (Ref. D-12) indicated no relationship between condition of trout and DO levels in that tailwater, nor any cyclic pattern of trout condiiton. A similar observation was made for trout data from a reach of the Little Tennessee River in eastern Tennessee, where DO levels also did not fall below 6 mg/L DO (H. D. Boles, personal communications).

On a monthly basis, LeCren condition of creeled fish from Norris tailwater are most strongly related to DO. However, comparison of the amount of seasonal decline in condition of creeled fish from summer to autumn showed no pattern in relation to abiotic parametres such as mean or minimum DO achieved during the low DO deficit period (DO less than or equal to 4.0 mg/L). Following initiation of a minimum flow in addition to aeration of releases, however, the annual cycling of trout condition was altered (Figures D-10 and D-11) during the three years (1985-1987) afterward.

Length / Weight Relationships. Length/weight relationships are another way of looking at fish growth in more statistically rigorous analyses. These relationships may reflect events in the life history of fish (Ref. D-7). Mathieson (Ref. D-13) reported that environmental conditions for a distantly-related salmonid, the sockeye salmon, were reflected in the length/weight regression. Hile (Ref. D-14) observed that annual and seasonal fluctuations in the length/weight relationships were so common as to be the general rule.

Through 1987, length/weight data were recorded from about 5,000 creeled rainbow trout from Norris tailwater. A 1985 analysis indicated that except for the seasonally low DO period occurring in the third quarter of the year, length/weight relationships of trout were generally better in the 1970's than following tailwater improvements in the 1980's (Ref. D-2). However, during the low DO period (third quarter), the length/weight relationship of trout was best after releases began being aerated 2-3 mg/L above the depressed scrollcase DO levels (1982-83). The "improvement" over values seen for the 1970's was not statistically significant. This minor improvement exhibited only during the period of low DO indicated that enhancement of DO in releases at the 2-3 mg/L level may have had a measurable, though brief and statistically non-significant, effect on trout growth during the low DO period. These measures of fish condition and benthic community characteristics may indicate that at this level of DO improvement we are approaching, but have not quite fully attained, a threshold of DO improvements providing biologically significant, measurable restoration of physico-chemical requirements for a more "healthy" stream ecosystem.

Creel Census. The relationships of fishing pressure, number of annual trips, catch rate, returns per cohort (group of fish of one known age or stocking), seasonality, discharge, air and water temperature, stocking schedules and size of trout stocked were reported by Yeager et al. (Ref. D-2).

Effort, catch rate and catch total (Figure D-13) increased during the years following aeration, but no changes appeared correlated with improvements or levels of DO, and were attributed to various other factors or each other. Expansion of the fishery is probably due to several factors, most particularly: public interest generated by TVA-TWRA efforts to enhance the trout fishery at Norris; the provision of more stable esthetically pleasing, "fishable" waters by maintenance of a minimum flow by the re-regulating weir; improved access in the tailwater; better information available to the public on flow conditions in the tailwater through a computerized, call-in river schedule program for all TVA tailwaters; establishment of an

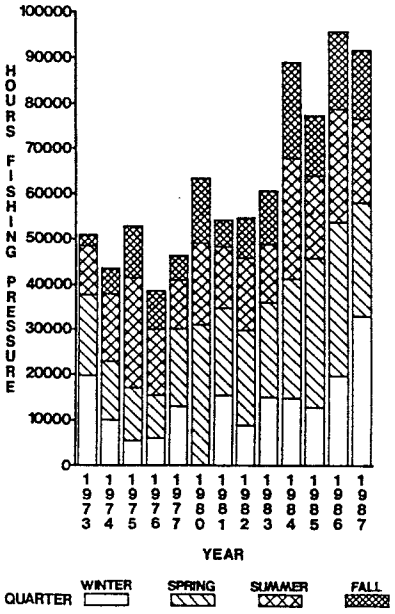


Figure 1a

FISHING PRESSURE

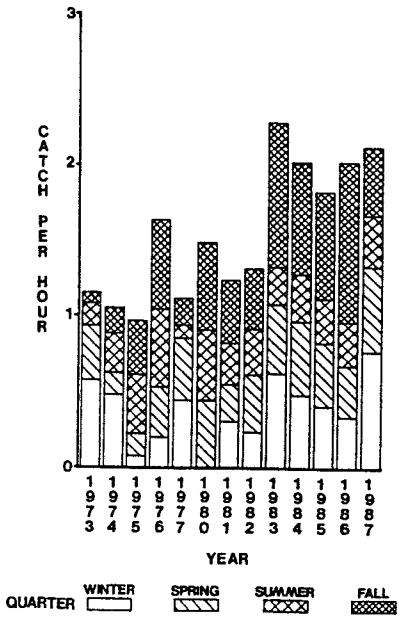


Figure 1b

TROUT CATCH RATES

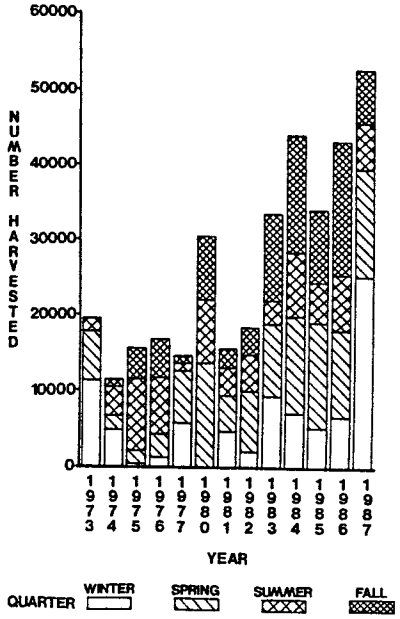


Figure 1c

TROUT CATCH TOTALS

Figure D-13. Fishing pressure, catch rates, and catch totals for Norris tailwaters.

improved stocking regime by the State of Tennessee; and the establishment of a trophy fishery for brown trout.

Survival. Survival for each known group of stocked fingerling trout appeared unrelated to DO concentrations (Ref. D-2). A linear regression of catch per unit effort (CPUE) through time after full recruitment for each fingerling cohort of rainbow trout was used to estimated survival. The decline in CPUE after a particular group of trout was fully recruited into the fishery was assumed to be related to abundance, therefore, the slope of the regression characterized the total mortality for each individual group of fish. A non-parametric Speerman rank correlation ($r = -0.54$) indicated survival and percent return of groups were not correlated, thus survival rates and improved DO levels could not be linked.

Summary. Two major problems associated with reservoir releases at many hydroelectric facilities in the United States have been discharge of water containing low DO concentrations and inadequate minimum flows. Both these conditions have adverse impacts on aquatic life downstream of Norris dam in the Clinch River. Releases from Norris dam have had DO concentrations as low as 0.6 mg/L, and no provision for minimum flows other than a small amount of leakage through the dam. TVA's Reservoir Releases Imrovements Program began addressing these problems through engineering "fixes" such as turbine venting now improving DO in releases 2-3 mg/L above scrollcase DO levels, and a re-regulating weir in conjunction with turbine pulsing to provide a 200 CFS minimum flow in the downstream regulated river.

Fishing effort, catch rate and harvest of trout increased significantly during aeration and following establishment of increased minimum flow, but were primarily due to better management of the tailwater (e.g., better stocking of the fishery, improved access and publicity) rather than directly to aeration and minimum flow. Historically, condition (plumpness) of trout in the tailwater cycled in a pattern coincident with DO cycling in dam discharges. During aeration years, length-weight relationships (as a measure of trout growth) were measurably improved, though not significantly so (statistical sense), during the low DO period. The pattern of annual

cycling of trout condition was not measurably altered solely by improvements at the 2-3 mg/L above scrollcase level achieved. Alterations of annual cycling were observed following establishment of a minimum flow and enhancement of DO levels.

No major shifts in macroinvertebrates occurred in the tailwater during aeration only. However, following both aeration and establishment of a minimum flow, desirable insect groups (e.g., mayflies, caddiflies and snails) became more widespread and frequent in the tailwater. Mayflies (relatively intolerant of low DO conditons) now consitute an important portion of the benthic fauna in the lower tailwater. These changes represent an initial response of the benthic community to improved DO and increased minimum flow. The slow, partial response of benthic macroinvertebrates may be due to DO levels still remaining below threshold levels required by many sensitive forms, or the scarcity of available colonizers.

These measures of fish condition and benthic community characteristics may indicate that at this level of DO improvement we are approaching, but have not quite fully attained, a threshold of DO improvements providing biologically significant, measurable restoration of physico-chemical requirements for a more "healthy" stream ecosystem.

Experiments On The Effects Of Constant And Fluctuating Dissolved Oxygen Levels Conducted At TVA's Aquatic Research Laboratory

Concern over the impacts on fishes and other aquatic life of seasonally low dissolved oxygen (DO) concentrations in the releases from a number of TVA reservoirs led the agency to conduct a series of experiments examining effects of low DO at TVA's Aquatic Research Laboratory (ARL) near Athens, Alabama. Experiments conducted at the ARL made use of both typical laboratory aquaria experiments and large-scale microcosms ("mesocosms") which more effectively simulate natural conditions. Four experiments were carried out in channels at ARL from 1984 through 1986 and one aquaria experiment in 1986. Experiments under conditions of either constant DO concentrations or fluctuating DO levels resembling those produced below a "typical" hydroelectric generating facility were conducted.

General Methods For Channel Experiments. For these experiments modifications were made to permit the large-scale use of nitrogen stripping of oxygen in up to seven (109.7-m x 4.27-m x 1.98-m) channels having alternating pool and limestone rock riffle (Figure D-14). Stripping of oxygen by bubbling nitrogen through the water column is a commonly used method (Ref. D-15 and Ref. D-16) for controlling DO level in experimental apparati. Flows were maintained at approximately 0.66 m^3/minute (180 gallons/minute) with velocities in pool areas approximately 0.14 m/minute. Water depth was maintained at 1.2-m in pools and 0.3-m over riffles. Sediment in approximately 7-m of the channel was removed down to the concrete floor. A 20-cm thick, 142-cm high wall was constructed 6 m downstream of the inlet. The top of this wall was approximately 56-cm below the top of the channel and acted as an underwater dam during operation. An array of 50, 114-cm x 8-cm Marox diffusers were placed about 30-cm above the concrete floor immediately upstream of the low block wall. A 300,000 cf liquid nitrogen tank, vaporizers and associated metering system was installed and connected to the diffusers via 1/2-inch copper tubing and associating fittings. Barrier screens (2-mm mesh) were installed in the channels 37.7-m downstream of the inlet and at the top of the underwater dam to confine test organisms. This area was termed the "experimental section" or "enclosure". Initial calculations suggested that sufficiently low DO concentrations could be maintained only in this area of the experimental channels.

A YSI 54 oxygen meter was used to measure DO in each section once in the morning (assumed to be daily minimum DO) and in the afternoon. Measurements were take 0.2-m deep immediately downstream of the underwater dam and at 0.3, 0.6, and 1-m deep just upstream of the barrier screen located at the downstream end of the enclosure.

Hardness, alkalinity, conductivity, and pH were taken in each enclosure twice during the experiment. Total gas pressure was measured in each enclosure with a Weiss Saturometer at the beginning and several times during the experiments. These measurements suggested no potential for gas bubble disease and no symptoms were observed.

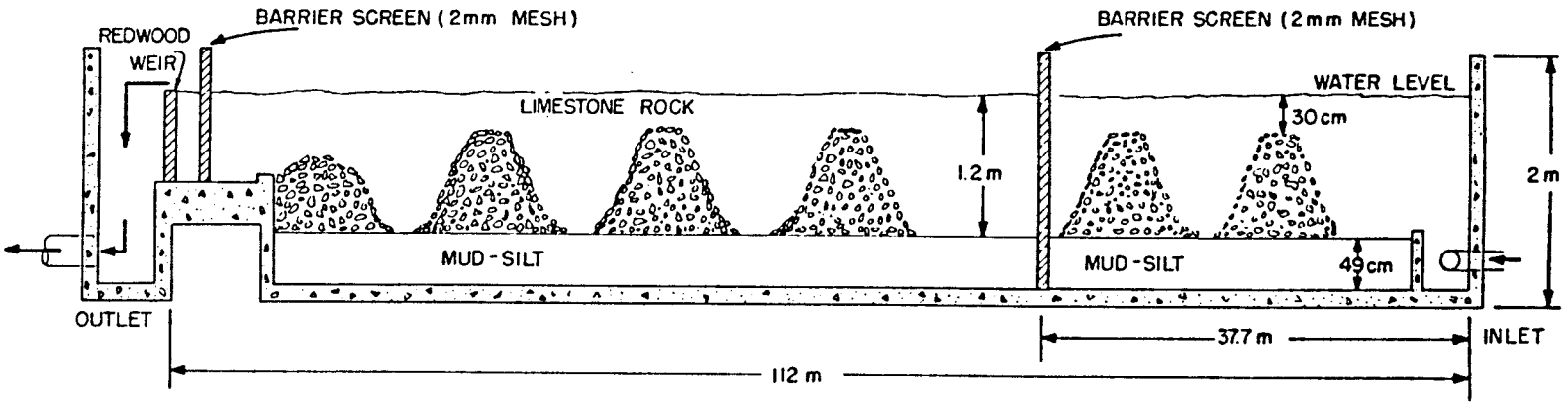


Figure D-14. Profile of experimental channel at TVA's Aquatic Research Laboratory at Browns Ferry Nuclear Plant, Alabama.

Effects Of Dissolved Oxygen Concentration On Mixed Fish And Invertebrate Assemblages In Large Experimental Channels

The first experiment began on June 29, 1984, when 200 smallmouth bass fry (average length 42-mm, average weight 0.6-g) were placed into each of six experimental sections of the channels. Twenty channel catfish (average weight by channel ranged from 28-34 g) were placed into each enclosure on July 3 and eight adult golden shiners (average weight 7.1-g) were stocked into each section on July 5. Bluegills (9.7-g average weight) were stocked 40 fish per section on July 19. However, high initial mortality of bluegill (apparently associated with handling stress) necessitated frequent restocking until numbers were stabilized at 30 fish per section by July 24. Two grass carp (average weight 140-g) were stocked to each enclosure on July 23. Grass carp were stocked to provide some control of the growth of rooted aquatic plants. Nitrogen stripping of oxygen from the water was begun on July 2 at a very low intensity and due to diffuser failure and modifications, treatment levels of 5, 4, 3, and 2 mg/L were not achieved until July 24. Nitrogen stripping of oxygen was discontinued during fish stocking. Dissolved oxygen concentrations returned to ambient in about 8 hours but establishment of equilibrium DO for a given rate of nitrogen gas flow took up to 24 hours.

Nitrogen stripping of oxygen was terminated on September 24. The experiment ran a total of 60 days from the time treatment levels were achieved. Final census was conducted using rotenone at 1.0 mg/L from October 1 through October 3, 1984. All fish were identified, counted, weighed and measured for length.

Minimum observed DO concentrations over the duration of the study for ambient, 5 mg/L, 4 mg/L, 3 mg/L, and 2 mg/L (two channels) treatment levels averaged 6.4, 5.1, 3.9, 3.5, and 2.4/2.2 mg/L; respectively. Actual concentrations within each enclosure had considerable daily and longitudinal fluctuation (Figures D-15, D-16). Dissolved oxygen concentrations over the entire length of the enclosures approximated target treatment levels for about 10 hours each evening. Mean DO concentrations extrapolated from daily DO curves were 7.0, 5.7, 4.6, 4.1, and 2.1 mg/L for the ambient through 2 mg/L treatments, respectively.

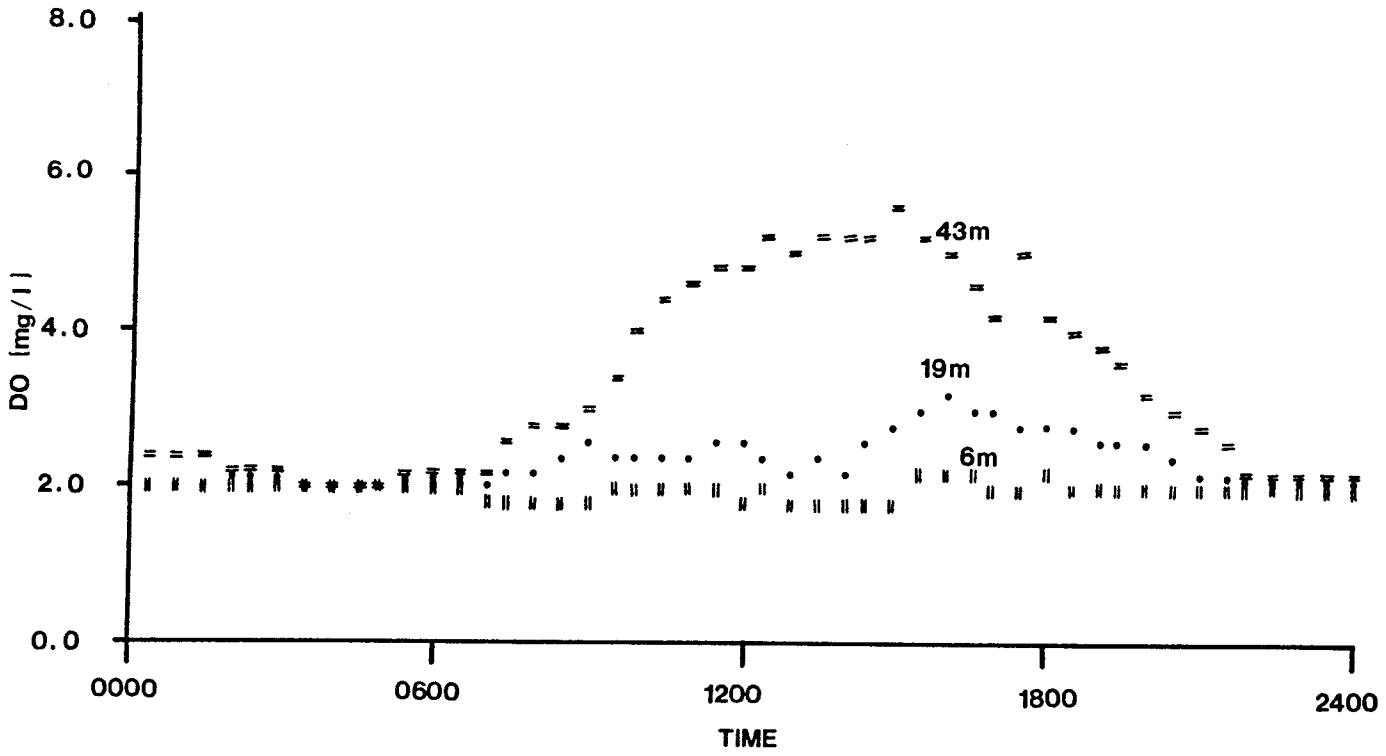


Figure D-15. Twenty-four hour DO curve at three positions in the experimental enclosure of the 2 mg/l nominal treatment level. Values taken every 1/2 hour at 0.3 m depth on August 22, 1984. Numbers above curve represent position in terms of distance from inlet.

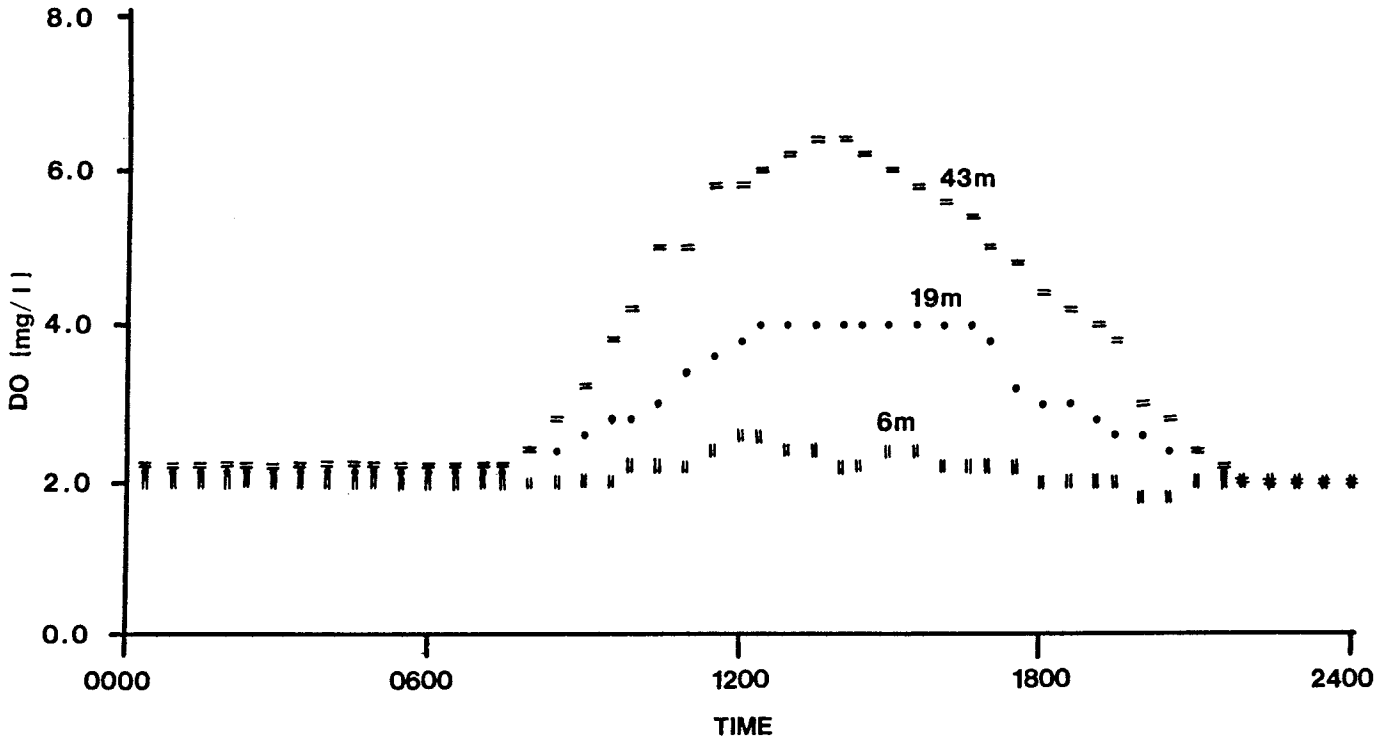


Figure D-16. Twenty-four hour DO curve at three positions in the experimental enclosure of the 2 mg/l nominal treatment level. Values taken every 1/2 hour at 0.3 m depth on August 23, 1984. Numbers above curve represent position in terms of distance from inlet.

Diurnal fluctuations in DO concentrations resulted from photosynthesis within the experimental enclosures. These daily fluctuations probably simulated fluctuations in natural ecosystems, however not neccessarily those expected from hypolimnetic releases in which tailwater DO concentrations also depend on discharge rates. For comparison of DO concentations achieved at ARL to the EPA criteria for juvnile and adult life stages of warmwater species (Ref. D-10), average minimum DO concentrations for the duration of this study were considered representative of the 7-day mean minimum, the minimum DO was considered equivalent with the daily minimum, and the 30-day mean DO was approximated based on extrapolation of the diel DO curves. The 4, 3, and 2mg/L treatments were below EPA's 30-day mean (5.5mg/L) and the seven-day mean minimum (4.0 mg/L) criteria for other life stages of warmwater fish species. The ambient and 5mg/L treatments were above EPA's criteria.

Significant findings from the study were: impaired production of smallmouth bass and golden shiners, as measured in final biomass, resulted from DO levels which violated the suggested USEPA DO criteria; survival of YOY smallmouth bass below ambient DO concentrations was poor (Table D-6); factors other than DO concentrations appeared to affect the final biomass in both bluegill and channel catfish; severe production impairment was observed for channel catfish at the 3 and 4 mg/L treatments while bluegill biomass were highest at these levels; bluegill spawning appeared to be impacted by reduced DO concentrations (Table D-7), this response does not agree with reported findings which generally show normal spawning by centrarchids at DO concentrations as low as 2 mg/L (Ref. D-17); predation appeared to limit the utility of multispecies testing of the effects of DO concentrations on spawning success; variability in response of macroinvertebrates to DO levels allowed no germane observations on relationships.

Continuous Exposure.

Rainbow Trout. Rainbow trout were exposed to DO target levels of 6, 4, and 2 mg/L in large (15 x 124 x 4-ft deep) outdoor channels at the Aquatic Research Laboratory for 80 days, from December 5, 1984, to March 6, 1985. Oxygen was stripped from inflow water using nitrogen. The oxygen stripping system did

Table D-6

TOTAL BIOMASS OF FISH RECOVERED FROM EXPERIMENTAL ENCLOSURES OF TERMINATION OF THE STUDY. REPLICATE CHANNELS FOR 2 PPM TREATMENT LEVEL ARE PRESENTED SEPARATELY.

		TREATMENT LEVEL				
Species	AMB	5	4	3	2	2
Channel Catfish	1111	893	610	579	930	1020
Golden Shiner (adult)	254	246	242	163	180	194
(YOY)	1	2	40	137	127	34
Mosquito Fish	0	15	2	0	0	0
Bluegill (adult)	711	693	938	800	746	730
(YOY)	192	0	0	0	0	0
Smallmouth Bass	111	45	14	0	17	0
Total	2380	1894	1846	1978	2000	1978
Gross Carp	3308	4020	--	--	2074	--

Table D-7

PRESENT OCCURRENCE OF MATURITY STAGES FOR ADULT BLUEGILL RECOVERED AT TERMINATION OF THE EXPERIMENT. DATA POOLED FOR 2 PPM LEVEL CHANNELS.

Treatment		Maturity Stage			
Level	N	I	D	R	S
Ambient	11	27	45	18	10
5 ppm	14	93	7	0	0
4 ppm	20	60	40	0	0
3 ppm	15	87	13	0	0
2 ppm	21	67	23	0	0

(N = Number; I = Immature; D = Developing; R = Ripe; S = Spent)

not function during an extreme cold weather period and this, along with fluctuation of DO levels in treatments caused by photosynthesis and respiration of algae in the channels, actually produced mean values of 7.9, 6.3 and 4.7 mg/L during the study (Table D-8). Water temperatures were generally low during the study (1-15°C) and growth was consequently slow. Significant findings from the study were:

Table D-8

SUMMARY OF RESULTS OF THE EFFECT OF VARIOUS DISSOLVED OXYGEN LEVELS ON RAINBOW TROUT GROWTH IN CHANNELS AT THE AQUATIC RESEARCH LABORATORY (December 5, 1984 - March 6, 1985)

Target DO mg/L	Range mg/L*	Mean mg/L	Weight Gain (Percent)
Control	11.5-13.0	12.3	84.6
6.0	7.0- 8.8	7.9	84.6
4.0	5.3- 7.2	6.3	82.0
2.0	3.5- 6.0	4.7	56.4

*Range of mean day DO values

1. EPA's proposed 30-day mean (6.5 mg/L), 7-day mean minimum (5.0 mg/L), and one-day minimum (4.0 mg/L) DO criteria for adult life stages of coldwater fish were not met during the 80-day test for the treatments with mean DO values of 6.3 and 4.7 mg/L.

2. Trout exposed to mean DO of 7.9 and 6.3 mg/L did not differ in their growth from the control.

3. Trout exposed to mean DO of 4.7 mg/L grew significantly slower than the control.

4. Fish in the control and 7.9 mg/L treatments fed more actively than fish exposed to lower concentrations.

Smallmouth Bass and Bluegill. A second study was conducted for 148 days, from April 12 through September 7, 1985, in the channels at the Aquatic Research Laboratory to determine the effect of low DO on reproduction, growth, and survival of smallmouth bass and bluegill. Brood fish were exposed to target DO levels of 4, 3, and 2 mg/L. DO fluctuated in the channels because of photosynthesis and respiration of algae and fairly wide fluctuations occurred (see Table D-9).

Table D-9

SPAWNING AND SURVIVAL OF SMALLMOUTH BASS AND BLUEGILL EXPOSED TO VARIOUS LEVELS OF DO (APRIL 12-SEPTEMBER 7, 1985). ADULT SMALLMOUTH WERE REMOVED AFTER 56 DAYS.

Treatment	DO Range mg/L	Spawning		No. of young fish in channel end of experiment	
		Bluegill	Smallmouth	Bluegill	Smallmouth
Control	4.2-11.0	yes	yes	0	228
Control	4.5-11.2	yes	yes	9	74
4 mg/L	1.7-13.0	yes	yes	430	35
4 mg/L	1.4-17.5	yes	yes	39	35
3 mg/L	1.7-12.6	yes	no	284	0
3 mg/L	0.5-11.2	yes	no	214	0
2 mg/L	0 - 9.9	yes	no	173	0

Smallmouth bass were removed after they had an opportunity to spawn (56 days). Reproduction of smallmouth bass was completely eliminated in the 2 and 3 mg/L treatment and was impaired in the 4 mg/L treatment. The bluegill sunfish spawned and survived well at all treatment levels, although egg mortality was very pronounced in the 2 mg/L treatment. Predation of young smallmouth bass reduced the numbers of bluegill, and they were completely absent from one control treatment at the end of the experiment.

Fluctuating Dissolved Oxygen.

Aquaria Experiments. Fingerling rainbow trout were exposed to fluctuating DO levels in aquaria at the Aquatic Research Laboratory to test DO effects on growth rate. Replicate 5-gallon aquaria were stocked with 10 four-inch rainbow trout and fish were exposed to four fluctuating DO levels which simulated conditions in hydro releases and continuous treatments of 3 and 5 mg/L and saturation (Table D-10). Fish were fed at the rate of 3 percent body weight per day during the 42-day test from January 16 to February 26, 1986, and trout growth was measured during the study.

Table D-10

GROWTH OF RAINBOW TROUT EXPOSED TO VARIOUS LEVELS OF DISSOLVED OXYGEN IN SMALL AQUARIA January 16-February 26, 1986[a]

	Daily Treatments	Replicate	Calculated Mean DO	Percent Weight Gain/Loss
1.	3 hr - 4 mg/L 3 hr - 5 mg/L 6 hr - 4 mg/L 12 hr - 7 mg/L	1A[b] 1B[b]	6.9 mg/L	16.0 30.8 (23.4)
2.	1 hr - 4 mg/L 5 hr - 6 mg/L 6 hr - 4 mg/L 12 hr - 7 mg/L	2A[b] 2B[b]	7.1 mg/L	22.5 23.5 (23.0)
3.	12 hr - 3 mg/L 12 hr - 7 mg/L	3A[b] 3B[b]	6.4 mg/L	4.4 15.0 (9.7)
4.	12 hr - 3 mg/L 12 hr - 7 mg/L	4A 4B	5.0 mg/L	16.6 11.3 (14.0)
5.	Continuous 3 mg/L	5A 5B	3.0 mg/L	0 -0.6 (-0.3)
6.	Continuous Saturation	6A 6B	11.0 mg/L	56.3 50.0 (53.2)
7.	Continuous 5 mg/L	7A 7B	5.0 mg/L	32.4 13.4 (22.9)

a. Mean percent weight gains of both treatments are shown in parentheses.

b. Saturday DO exposure is 4 hours at 3 mg/L and Sunday 2 hours at 3 mg/L; balance on Saturday and Sunday is saturation.

There was not mortality in any of the treatments. Findings from these studies were:

1. Decreases to 4 mg/L for periods of 7 and 9 hours for 5 days per week and 3 mg/L for 4 hours on Saturday and 2 hours on Sunday (treatments 1 and 2) resulted in growth rates equivalent to the continuous 5 mg/L. This comparison is useful in considering a potentially cost-effective, operational schedule of hydropower releases (variable DO) with a fixed numerical crite-

ria. Conceivably, turbine releases with only 4 mg/L (in conjunction with higher DO levels during periods of the day when releases are not made) may be equivalent biologically to a fixed 5 mg/L criteria. Even though the minimum daily DO was 4 mg/L for treatments 1 and 2, the mean DO concentrations (6.9 and 7.1 mg/L) were higher than the fixed 5 mg/L.

2. Fish grew better when DO was 5 mg/L continuously than when DO was variable between 3 and 7 mg/L but with the same mean concentration of 5 mg/L. Trout grew an average of 22.9 percent in the continuous 5 mg/L treatments, but only 14 percent in treatments with 12 hours each day of 7 and 3 mg/L.

3. Brief increases in concentrations produced by a simulation of weekend hydro operations did not increase growth rates. Fish exposed to 42 hours of saturated DO and 12 hours each of 3 and 7 mg/L for the other 5 days of the week (treatment 3) actually grew slower (9.7 vs. 14.0 percent) than trout exposed to the 12-hour splits each day for 7 days per week (treatment 4). However, this scenario warrants further investigation.

Channel Experiments. A set of trout growth experiments were conducted in the outdoor channels at the Aquatic Research Laboratory based on findings from these aquaria studies for 37 days from February 18 to March 26, 1986. Each channel was stocked with 90 fish similar in size to those used in the previous experiment. Changing DO concentrations which simulate hydropower operations were also used. Results are shown in Table D-11. In channel experiments, exposure of fish to saturation concentrations on weekends increased growth (136.5 percent vs. 67.7 percent) and survival (83.3 percent vs. 71.1 percent) over that of trout exposed to 10 hours at target concentrations of 3 and 14 hours at 7 mg/L daily over that during the 37-day test. This observation was inconsistent with the observation from the aquaria studies and warrants further investigation.

The results of these latter aquaria and channel studies indicate that brief decreases in DO to 4 mg/L for periods of 7 to 9 hours per day for 5 days each week and to 3 mg/L for 2 to 4 hours on weekends (with mean 7-day DO concentrations of 7 mg/L) yield growth rates equivalent to those observed when DO was maintained at a constant 5 mg/L. This finding (if confirmed by additional research) is significant because

many hydropower plants are operated only several hours each day, and DO typically is much higher in the tailwater when there is no hydropower generation. For example, at Norris 4 mg/L in the turbine discharge may be sufficient because when turbines are not operating, DO is usually about 7 mg/L. The cost of providing 4 mg/L is about one-half of that required for 5 mg/L.

Table D-11

GROWTH OF RAINBOW TROUT EXPOSED TO VARIOUS LEVELS OF DISSOLVED OXYGEN IN LARGE OUTDOOR CHANNELS AT AQUATIC RESEARCH LABORATORY February 18 to March 26, 1986

	Daily Treatments	Mean DO mg/L	Range m/g L	Percent Survival	Weight Gain(%)
1.	Control	10.6	6.9-15.8	96.7	158.4
2.	Control 185.3	10.0	6.8-13.6		82.2
3.	10 hr - 5 mg/L 14 hr - 7 mg/L saturation - Sat/Sun	7.4	3.1-12.6	86.7	153.9
4.	10 hr - 4 mg/L 14 hr - 7 mg/l saturation - Sat/Sun	6.8	2.8-13.6	78.9	122.6
5.	10 hr - 3 mg/L 14 hr - 7 mg/L	5.0	2.2-12.2	71.1	67.7
6.	10 hr - 3 mg/L 14 hr - 7 mg/L saturation - Sat/Sun	6.4	2.0-15.2	83.3	136.5
7.	Continuous 5 mg/L	6.1	3.3-16.0	90.0	124.2

Appendix E

FEIS: UPPER OHIO RIVER BASIN

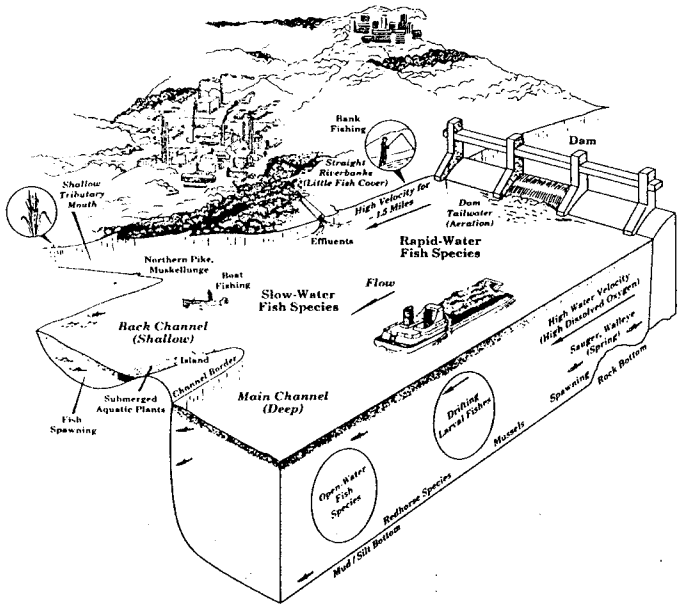
The following material is an excerpt from the FERC document Hydroelectric Development in the Upper Ohio River Basin, Final Environmental Impact Statement, and is included in support of Section 4 of this manual.

FERC/FEIS-0051

HYDROELECTRIC DEVELOPMENT
IN THE
UPPER OHIO RIVER BASIN
FERC Docket No. EL85-19-114

Ohio, Pennsylvania, West Virginia

FINAL
Environmental Impact Statement



Federal Energy Regulatory Commission
Office of Hydropower Licensing

September 1988

EXECUTIVE SUMMARY

This final environmental impact statement (FEIS) evaluates potential environmental impacts of up to 19 hydropower projects in the upper Ohio River Basin. The Federal Energy Regulatory Commission (FERC) is considering license applications for 24 projects, which are proposed at 19 existing dams on the Allegheny, Monongahela, Tygart, Muskingum, and Ohio rivers (5 sites have competing applications). All of the projects are proposed at navigation dams, except the two competing projects at Tygart Dam. All of the dams are operated by the U.S. Army Corps of Engineers (Corps) except Muskingum Lock and Dam (L&D No. 3), which is operated by the Ohio Division of Parks and Recreation.

The action of licensing multiple hydroelectric projects in the upper Ohio River Basin involves tradeoffs between new energy production and environmental quality. The alternatives considered in this FEIS were developed by the staff (1) to give equal consideration to power generation and environmental quality values, in accordance with the Electric Consumers Protection Act of 1986 (Pub. L. 99-495) and the National Environmental Policy Act of 1969 (Pub. L. 91-190), as amended, and (2) to respond to concerns raised during the scoping process.

The staff has analyzed both cumulative and site-specific impacts that would occur to target and other environmental resources. The target resources related to hydroelectric development in the upper Ohio River Basin that were defined during scoping are water quality, fisheries, recreation, wetlands, and river navigation. The staff has also evaluated impacts to other, nontarget resources, including land use, endangered and threatened species, historic and archaeological resources, aesthetics, and socioeconomics.

The alternatives include four different ways of developing hydropower resources, ranging from production of all the proposed power with little environmental protection to producing 82 percent of the proposed power while causing no major environmental impacts. Other alternatives that are considered include producing electricity with a coal-fired power plant (the non-hydroelectric generation alternative), nongenerating alternatives, and licensing none of the projects (the no-action alternative).

Alternative 1 entails constructing and operating projects at each of the 19 sites as proposed by developers in their license applications. Mitigation, including spill flows and recreation facilities, are those proposed by applicants following consultation with resource agencies. Alternative 1 would cause major impacts to water quality, fisheries, recreation, and wetlands. Dissolved oxygen (DO) concentrations that would be toxic to, or would reduce the growth of, many species of fish would result. Significant reductions in the recently improved fisheries of the Ohio River Basin could occur, with resulting reductions in the quantity of recreational fishing. Three projects (Allegheny L&D No. 7, Montgomery, recreation, L&D, and Muskingum L&D No. 3) would cause significant adverse impacts to important fish habitat, recreation, and wetlands, with a net loss of at least 7 acres of wetlands. Benefits to recreation would result from development of fishing access at power plant tailrace areas, and socioeconomic benefits would result from increased employment during construction.

Alternative 2 maintains state DO standards but does not maximize the protection of the fisheries resource. This alternative involves modifying operations of projects built at the 19 sites to ensure that the state DO standard of 5 mg/L in Pennsylvania, West Virginia, and Ohio would be met wherever and whenever possible. This objective would be accomplished by requiring projects at Allegheny L&D No. 2, Emsworth, Dashields, Montgomery, New Cumberland, and Pike Island to cease operations when flows in the Ohio River fall below 9000 cubic feet per second during the period July through October. Overall, the impacts of Alternative 2 would be very similar to those of Alternative 1. Reductions in DO would occur that do not violate standards but still significantly affect aquatic life. Impacts to fisheries, recreation, and wetlands would be similar to those under Alternative 1. Benefits to recreation would result from development of fishing access at power plant tailrace areas, and socioeconomic benefits would result from increased employment during construction.

Alternative 3 protects water quality by modifying project operations to avoid degradation of water quality that would affect aquatic life. The objective of this alternative is to maintain DO concentrations at 6.5 mg/L where possible to ensure that hydroelectric development will not adversely affect the fishery resources. This alternative responds to comments received during the scoping process to the effect that hydropower projects must maintain existing DO conditions downstream from the project dams. Alternative 3 would eliminate significant adverse impacts to water quality by requiring spill flows sufficient to provide DO concentrations greater than or equal to 6.5 mg/L, while maximizing basin-wide power generation. Significant water quality impacts to fisheries and recreation would not occur. Mitigation for

the water quality, fisheries and recreational target resources would be implemented. Major adverse impacts to fish habitat, recreation, and wetlands would still occur at three sites. Benefits to recreation would result from development of fishing access at power plant tailrace areas, and socioeconomic benefits during construction would result from increased employment during construction.

Alternative 4 maximizes protection of all target resources by developing 16 projects that do not cause significant unavoidable impacts. Cumulative impacts of these 16 projects are evaluated. The staff's recommended spill flows to maintain DO concentrations at or above 6.5 mg/L apply. Alternative 4 would avoid major adverse impacts to fish habitat, recreation, and wetlands. Because these major impacts are concentrated at only three sites (Allegheny L&D No. 7, Montgomery L&D, and Muskingum L&D No. 3), they can be avoided by not developing these sites for hydropower. Mitigation for all target resources would be implemented. A comparatively small decrease in the generating capacity of the basin would result from this alternative. Benefits to recreation would result from development of fishing access at power plant tailrace areas, and socioeconomic benefits would result from increased employment during construction.

The staff believes that a 400-MW coal-fired steam plant or plants would be the most likely non-hydroelectric generating alternative to the proposed hydroelectric projects. The impacts of the coal-fired power plant would involve releases of sulfur dioxide, oxides of nitrogen, and water vapor. The impacts would be site specific, depending upon the dispersive capability of the local atmosphere, other local sources of air pollutants, and regional concentrations of the pollutants released by the unit. Compliance with regulations for the Clean Air Act of 1970, as amended, would ensure that air-quality impacts from unit operation would be analyzed and found to be acceptable. Unit operation would, however, increase regional pollution levels and contribute to air-quality-related problems such as acid rain and regional ozone levels.

The principal nongenerating alternatives to the proposed projects are conservation and load management to reduce energy requirements and to reduce peak demands for capacity. Although environmental impacts of such alternatives are less than those associated with building and operating new hydroelectric units, implementation of such measures has, in many cases, been pushed to the limit of cost-effectiveness. For this reason, the nongenerating alternative cannot be assumed to be available.

The nonhydroelectric generating alternatives and the nongenerating alternatives would allow no development of the upper Ohio River Basin's hydropower potential. Although impacts to the target resources evaluated in this FEIS would be avoided by these alternatives, other impacts to the environment would occur from power generation using other sources if these alternatives were selected.

The no-action alternative would constitute a denial of all the applications for license to construct, operate, and maintain the proposed projects. This alternative would result in the nonuse of potential energy that could be derived by developing the proposed sites and in the consumption of fossil fuel that would be saved if the proposed projects were developed.

Staff has conducted economic analyses for each project, under each of the alternatives. These alternatives would have different spill flows at each site and, therefore, allow various amounts of generation during critical periods. Under Alternative 1, projects at all of the sites would have positive net economic benefits.

Projects at all of the proposed sites would also have positive net economic benefits under Alternative 2. This second alternative would provide approximately 1900 gigawatt-hours (GWh) of energy, 10 GWh less than Alternative 1.

Under Alternative 3, the increased spill requirement at Montgomery L&D would limit the economic benefits at the site and make that project feasible only under a favorable combination of interest rates, construction costs, escalation rates, and other factors. At least one project at all of the other sites would be economically beneficial. The amount of energy available under this third alternative would be approximately 1760 GWh or 150 GWh per year less than with the Alternative 1. Projects at 7 of the 19 sites would have their energy reduced by at least 10 percent under Alternative 3 as compared with Alternative 1. Alternative 3, however, does avoid significant adverse impacts to water quality and subsequently to fisheries and recreation. Staff estimates that the value of the energy lost by Alternative 3 would be worth about 12 million dollars per year at a levelized rate of approximately 8 cents per kilowatt-hour.

however, would avoid major adverse impacts to water quality, fisheries, wetlands, and recreation. This alternative would reduce the total generation available under Alternative 1 by a total of 350 GWh per year. The cost of the energy lost would be approximately 28 million dollars per year.

From its environmental analysis, the staff recommends Alternative 4 as its preferred alternative for development of hydropower projects in the upper Ohio River Basin. Sixteen hydropower projects would be constructed and operated with staff's recommended mitigative measures to avoid or minimize significant environmental impacts. This alternative allows generation of about 82 percent of the power proposed by project applicants but prevents projects from causing DO concentrations low enough to significantly affect aquatic life. Proposed hydropower projects would not be developed at Allegheny L&D No. 7, Montgomery L&D, and Muskingum L&D No.3 to avoid significant adverse impacts to wetlands, fish, and recreation at these sites. The recreational enhancements these three projects could provide cannot compensate for losses of important habitat. However, staff recommends that additional mitigative measures that could reduce impacts of these three projects be studied. The protection of wetlands and fish habitat provided by Alternative 4 is important for maintaining the overall biological integrity of the basin.

Table 1.2-1 (concluded).

1/ Abbreviations:
AEP = American Electric Power Co., Inc.
APS = Allegheny Power System, Inc.
GPU = General Public Utilities Corp.
MECS = Michigan Electric Coordinated Systems
MAAC = Mid-Atlantic Area Council
ECAR = East Central Area Reliability Coordination Agreement
VACAR = Virginia - Carolina Power Area of the Southeastern Electric Reliability Council

It is appropriate to state that because the development of hydroelectric capacity has been encouraged at sites which are equally important for reasons other than the generation ofelectric power, such as flood control, irrigation, and river navigation, the proposed hydroelectric developments in the Ohio River Basin represent a component of the projected IPP capacity with a higher degree of certainty. The electricity produced by these facilities generally adds very little additional impact and is produced at a cost below that of other generating resources. Water-entrained energy, which would otherwise be wasted, can be captured to conserve non-renewable primary energy resources and to reduce atmospheric pollution.

Longevity of project operation, a utility concern in the case of some IPP projects, is not a serious concern in the case of hydroelectric IPP facilities constructed at sites having a second important purpose.

Between 400 and 480 MW of base-load capacity from the proposed Basin projects would be useful to regional utilities because the base-load energy produced by these projects would displace energy produced by inefficient coal-fired, load-following units (stacked above the base-load units) by increasing base-load capacity.

1.3 SCOPE OF THE FEIS

The staff prepared an environmental assessment (EA) for the Ohio River Basin (FERC, 1987a) that concludes that the proposed projects would interact with one another in a manner that would contribute to significant cumulative adverse impacts to target resources, which were identified as dissolved oxygen, recreational fishing, and river navigation. From the analysis in the EA, the staff determined that the proposed construction and operation of multiple hydropower projects in the basin warranted the preparation of an EIS to address the site-specific and cumulative environmental impacts of licensing the proposed projects.

The staff's review of existing water quality data and information on other resources indicated that additional information was needed to conduct cumulative and site-specific analyses. Therefore, FERC staff requested that the applicants conduct additional studies and held a meeting on July 20, 1987, with the applicants and their consultants in Pittsburgh, Pennsylvania, to provide guidance on conducting field studies to obtain the necessary information.

Scoping meetings and public hearings to obtain comments on the scope of the FEIS and the issues to be addressed were held by the staff in Pittsburgh, Pennsylvania, on June 11, 1987, and in Huntington, West Virginia, on June 17, 1987. The results of comments made during the scoping process, were published in Scoping Document II (FERC, 1987b), dated August 10, 1987, to identify the issues to be addressed in the EIS. The scoping process also involved a series of formal and informal interactions with applicants, licensees, state and federal agencies, and interested persons. A technical meeting was noticed and conducted on September 17, 1987, in Pittsburgh, Pennsylvania, to allow staff to provide an update of the progress on the draft environmental impact statement (DEIS) and to present the analytical procedures to be used. Informal meetings were also conducted in Grafton, West Virginia, on November 3, 1987, concerning recreational fishing issues, and in Charleston, West Virginia, on December 8 and 9, 1987, concerning fish entrainment issues. The staff has also participated in project site visits and meetings with representatives from the Corps and has provided information at Ohio River Valley Water Sanitation Commission (ORSANCO) technical sessions and meetings related to the status of the EIS studies.

In defining the geographic scope of this study, staff considered the location and licensing status of all existing and potential hydroelectric facilities in the Ohio River Basin

(FERC, 1987a). There are 113 existing and potential hydroelectric projects identified in FERC's Hydroelectric Power Resources Assessment data base as of February 1988, including 24 projects in operation, 17 pending projects that have been issued licenses, 3 pending projects that have been issued license exemptions, 28 projects for which license applications have been accepted, and 41 projects with preliminary permit applications or outstanding peliminary permits (Figure 1.3-1). The highest concentration of projects is in the upper part of the river basin, on the main stem of the Ohio River and its two major tributaries, the Allegheny and Monongahela rivers.

After reviewing the information developed during the scoping process, the staff determined that the projects and cumulative impact study area originally proposed in the Ohio River Basin EA encompass the most concentrated stretch of proposed hydropower development in the Ohio River Basin. Staff believes that including additional proposed projects, as suggested by several commenters, would increase the complexity of the analysis without contributing to an understanding of cumulative impacts. The study area in the FEIS, therefore, includes the river mile (RM) reach of the following rivers: 20 miles of the Tygart Valley River; 128.7 miles of the Monongahela River; 45.7 miles of the Allegheny River; 14.2 miles of the Muskingum River; and, to the pool formed by the Greenup L&D that is located downstream from the pending competing projects at Gallipolis L&D at RM 279.2 on the Ohio River.

In addition to the 19 dams where hydropower projects have been proposed in the upper basin, there are 5 dams with no pending license applications (Monongahela L&D Nos. 2, 3, and 7; Morgantown L&D; and Muskingum River L&D No. 2) and 6 dams where hydropower licenses have been issued by FERC [Allegheny River L&D No. 5 (FERC No. 3671), Allegheny River L&D No. 6 (FERC No. 3494), Allegheny River L&D Nos. 8 and 9 (FERC No. 3021, Hannibal L&D (FERC No. 3206), and Racine L&D (FERC No. 2570)] (Figure 1.1-1). Because these 11 dams have important interactions with the proposed hydropower projects, they are evaluated in the water quality modeling portion of the FEIS. The total number of dams considered in the FEIS is 30, distributed over 500 river miles of the Allegheny, Monongahela, Tygart, Muskingum, and Ohio Rivers.

Since the preparation of Scoping Document II (FERC, 1987b), the competing application at Montgomery L&D (FERC No. 3490) and the competing application at Willow Island L&D (FERC No. 9999) were dismissed. The dismissals are currently under appeal by the applicants. In addition, prior to issuance of the DEIS, an application for a hydropower project at Morgantown L&D (FERC No. 9949) was filed with the Commission. The application was determined to be deficient and the applicant has been informed of these deficiencies. Staff used available information to analyze the contribution to cumulative impacts to water quality and fishery resources in the EIS study area attributed to hydropower development at the Morgantown dam site. At this time, information needed to evaluate all environmental impacts (site-specific and cumulative) associated with hydropower development at Morgantown is not available, and an assessment of these impacts is not included in the present study. Analysis of these impacts will be provided, as needed, in future environmental assessment documents tiered to this EIS.

From the discussions and comments generated during the scoping process, the staff has identified the following issues that are addressed in this FEIS:

1. Impacts on water quality and hydraulics caused by changes in aeration, water depth, currents, and volatilization of pollutants from the rivers.

2. Impacts on fishery resources resulting from changes in dissolved oxygen, altered flow patterns, and turbine-induced fish injury and mortality.

3. Impacts on recreational fishing resulting from changes in fish populations, and the effects of construction, structures, and flow modifications on river access and navigation.

4. Socioeconomic impacts, including effects of construction on the regional labor force, and social and economic effects of construction and operation.

5. Effects of dredge spoil disposal.

6. Impacts on archaeological and historic resources, including disturbance of unknown prehistoric and historic sites during construction and dredge spoil disposal.

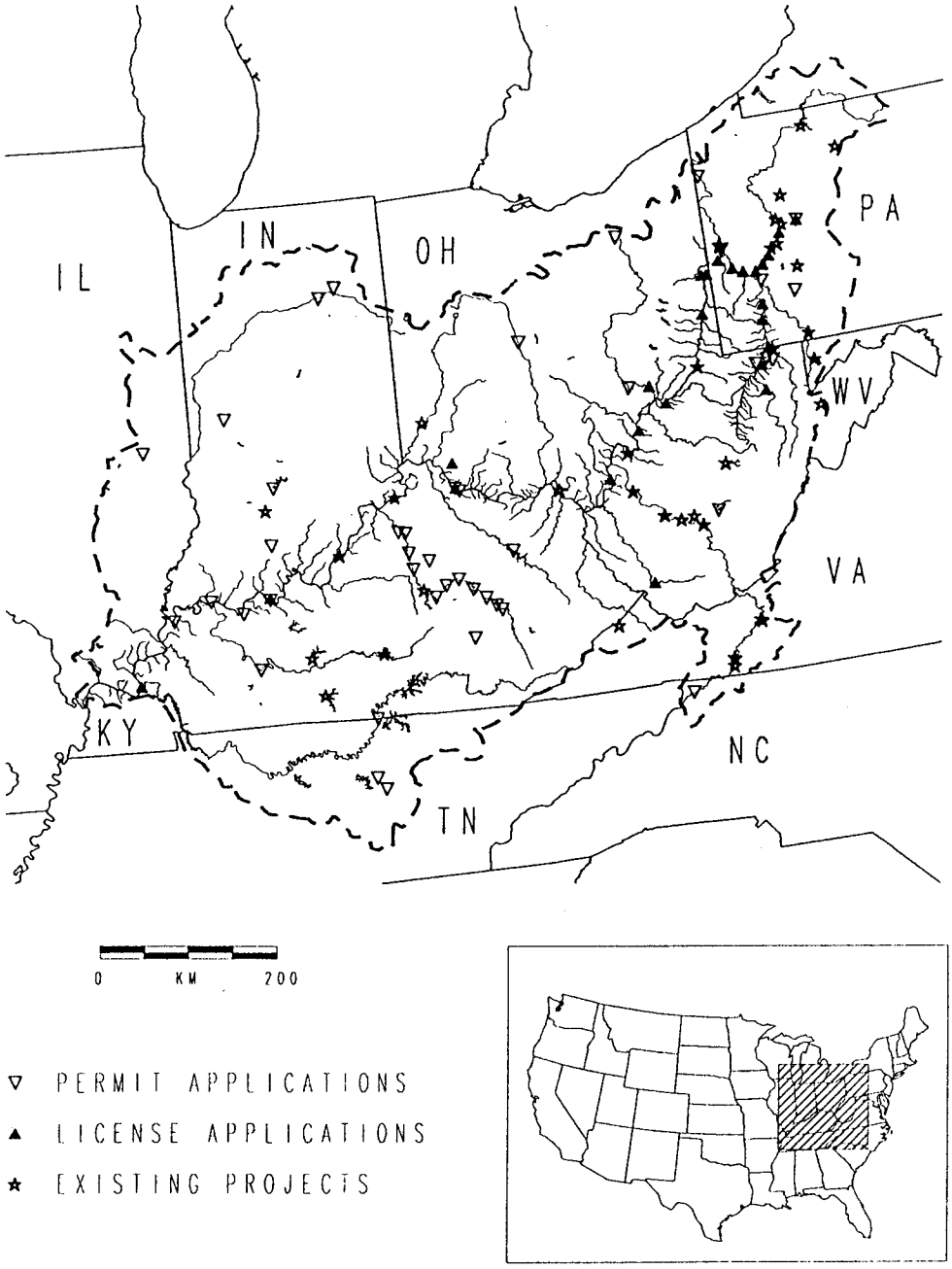


Figure E-1. Potential and Existing Hydroelectric Projects in the Ohio River Basin. Source: Staff Analysis of FERC's Hydroelectric Power Resources Assessment Data Base.

7. Impacts on terrestrial resources, including loss or modification of wetlands and other wildlife habitat from project construction and operation of project facilities, such as transmission lines, access roads, dredge spoil disposal areas, and other facilities.

8. Impacts on aesthetic resources from changes in physical factors contributing to landscape quality.

A draft environmental impact statement (DEIS) was made available to the public on May 10, 1988. Comments on the DEIS received by FERC have been considered by modifying the text or responding in Appendix J of this FEIS.

1.4 PROJECT INTERACTIONS AND CUMULATIVE EFFECTS

Although many of the potential impacts from hydroelectric development in the Upper Ohio River Basin are site specific and do not have the potential for interactions among sites, interactions and cumulative impacts have been identified as a major concern. The primary mechanism for project interactions and cumulative effects is by diversion of flow through turbines at navigation dams and subsequent impacts to water quality, river hydraulics, fish populations, and recreational fisheries.

The proposed actions evaluated in this FEIS are all retrofits of hydroelectric generation capacity into existing dams. With the exception of the Tygart Dam project, all the proposed projects are located at existing, low-head navigation dams. River flow has three ways to pass navigation dams prior to the installation of hydroelectric facilities:

(1) Spillage -- water can spill over the dam crest or through the open gates,

(2) Lockage -- water can be passed through the navigation lock, or

(3) Leakage -- water can leak through the dam, the gates or the lock.

Installation of hydroelectric facilities introduces a new route for water to pass the dam, through the hydroelectric turbine. The diversion of river flow through the turbine results in a reduction in spillage because lockage requirements must still be satisfied and leakage will remain relatively constant. Reduced spillage and the concentration of dam discharge in the turbine's tailrace are the major causes of potential adverse environmental impacts from the proposed projects. These and other potential concerns resulting from hydropower retrofits have been described by Schmitt and Varga (1988).

Reduced spillage and altered tailwater flows initiate a chain of impacts affecting water quality, aquatic biota, and fishery resources (Figure 1.4-1). Water spilled at dams, especially fixed-crest dams, undergoes aeration. In large rivers that receive heavy wasteloads from point-source dischargers, such as the mainstem of the Ohio River, aeration at dams can be an important component of the overall dissolved oxygen budget. Therefore, the loss of some spillage can be a threat to a river's water quality. Reduced spillage can also reduce the upstream water surface elevation because the depth of water flowing over the dam is reduced. This issue of reducing upstream pool elevations is important only at fixed-crest dams; at gated structures, the gates can be operated to maintain a constant upstream pool elevation. During low-flow periods, reduced pool elevations may dewater or degrade aquatic habitat, depending on the magnitude of the elevation change.

A cumulative impact can be described as an environmental change that results from the accumulation and interaction of the effects of one action with the effects of one or more other actions occurring on a common resource (Reed et al., 1984; Stull et al., 1988). The effect on dissolved oxygen (DO) of developing multiple hydroelectric projects has been documented in large river systems (e.g., USEPA, 1985) and is an excellent example of cumulative impacts. As illustrated in Figure 1.4-2(a), the aeration that occurs in spillage can cause discrete jumps in a river's longitudinal profile of DO concentrations. The construction and operation of new hydro projects can eliminate these DO jumps and cause DO concentrations to drop below water quality standards [Figure 1.4-2(b) and (c)]. The combination of reduced aeration at two or more successive dams can aggravate the water quality problems even more, as DO concentrations sag further below a standard for more miles of river [Figure 1.4-2(d)]. These impacts to water quality are cumulative and complex.

Cumulative impacts can be quantified to various degrees, depending on their mode of action and the complexity of their effects. Fortunately, the art of water quality modeling is sufficiently developed that cumulative impacts from reduced spillage and aeration can be predicted relatively well. A simulation model of DO was developed as part of this analysis to address some of the cumulative impact concerns. Other cumulative effects, such as the impacts to fish populations, are much more difficult to quantify. Effects to fish populations result from multiple causes: lower DO, modified habitat, and mortality of fish entrained into hydroelectric turbines (Figure 1.4-1). The response of populations to multiple stresses is difficult to predict because most natural populations have excess reproductive capacity which can compensate for some losses of individuals (e.g., Barnthouse et al., 1984). To the degree possible, cumulative effects are evaluated with quantitative methods in this FEIS. Where they cannot be predicted, they are discussed in qualitative terms, and unknowns and uncertainties are identified.

Appendix F

EXAMPLE: TOTAL PRESENT WORTH AND SENSITIVITY ANALYSIS

When several aeration techniques are capable of meeting a particular dissolved oxygen deficit, the principal deciding factor when choosing the final technique is usually economics. As discussed in Section 2, many elements are considered when estimating the cost of a specific technique. These include initial installation, the yearly operating costs of energy and oxygen, manpower, interest on the investment, lost power revenues, replacement power, and additional maintenance. The individual cost of each item can be estimated over the life of a system, and either of two economic methods of comparison can be made: Total Present Worth, or Equivalent Uniform Annual Cost. The Total Present Worth method converts each cost incurred throughout the life of the system to its present-day value. The sum of these values is the Total Present Worth.

The second method of economic comparison, the Equivalent Uniform Annual Cost, converts each cost to a series of uniform payments over the life of the system. The sum of the payments for a single year is the Equivalent Uniform Annual Cost.

Both methods, if performed correctly, will arrive at the same conclusion. Equivalent Uniform Annual Cost can be calculated from Total Present Worth by multiplying the latter by the appropriate capital recovery factor, and Total Present Worth can be calculated from Equivalent Uniform Annual Cost by multiplying by the appropriate series present worth factor (Ref. F-1). However, because many of the costs incurred are periodic in nature and of a variable frequency, it is recommended that the Total Present Worth method be used to compare techniques. For example, the initial installation may be funded with borrowed money, having a payback period of ten years. Diffusers may need maintenance once every 3- to 6-years, and replacement every 8- to 12-years. Compressors may need major overhauls once every 10- to

20-years. Additional runner maintenance may be required every other year. Because the periods vary, it is not only easier to calculate the Present Worth of each item, but may also be less misleading. The following example will illustrate the method.

Example: Total Present Worth

Assume that the following costs are estimated for an oxygen diffuser system that incorporates a Pressure-Swing-Absorption (PSA) system (40-year life expectancy) as an oxygen supply:

Initial Costs:

Diffusers	$12,000
Distribution Piping	8,000
40-ton/day PSA plant	1,000,000
Installation (labor)	90,000
Total Initial Cost:	$1,110,000

Annual Operating Costs:

Energy	$135,000
Labor	10,000
Insurance	28,000
Maintenance	10,000
Power generation loss	0
Replacement Power	0
Total Annual Cost:	$183,000

Periodic Maintenance:

Compressor overhaul (every 10-years)	$8,000
Diffuser cleaning (every 5-years)	22,000
Diffuser replacement (every 10-years)	15,000

The Present Worth of the initial installation is $1,110,000. The annual operating costs are converted to a Present Worth by using the Uniform Series Present Worth Factor (P/A) for the proper interest rate and period. In this case, the interest is assumed to be 12%, and the period is the life of the system (40-years), and the P/A is 8.244 (Ref. F-1). Periodic maintenance charges for compressor overhauls, diffuser cleaning, and diffuser replacement occur at year 5, 10, 15, 20, 25, 30, and 35. Each of these costs can be considered as lump sums, and each reduced to a Present Worth by multiplying by the respective Single Payment Present Worth Factor (P/F).

Assuming the initial installation cost ($1,110,000) must be borrowed at an annual interest rate of 12% and a the payback period is 10-years, annual loan payments would be $196,448 per year. The cash flow over the 40-year lifespan is depicted in Table F-1.

Total Present Worth Calculation:

Initial Installation	$1,110,000
Present Worth of a series of payments, $183,000 at 12% for 40 years	1,508,652
5 yr Periodic Maintenance	12,483
10 yr Periodic Maintenance	7,406
15 yr Periodic Maintenance	4,019
20 yr Periodic Maintenance	1,697
25 yr Periodic Maintenance	1,294
30 yr Periodic Maintenance	768
35 yr Periodic Maintenance	416
Total Present Worth	$2,646,735

Table F-1

ANNUAL COSTS INCURRED FOR WORKING EXAMPLE

Year	Cost	Year	Cost
1	$379,448	21	183,000
2	379,448	22	183,000
3	379,448	23	183,000
4	379,448	24	183,000
5	401,448	25	205,000*
6	379,448	26	183,000
7	379,448	27	183,000
8	379,448	28	183,000
9	379,448	29	183,000
10	402,448x	30	206,000x
11	183,000	31	183,000
12	183,000	32	183,000
13	183,000	33	183,000
14	183,000	34	183,000
15	205,000*	35	205,000*
16	183,000	36	183,000
17	183,000	37	183,000
18	183,000	38	183,000
19	183,000	39	183,000
20	206,000x	40	183,000

* - denotes year diffusers were cleaned
x - denotes year in which compressors were over-hauled and diffusers replaced

To convert Total Present Worth to Equivalent Uniform Annual Payments, multiply the Total Present Worth by the appropriate Capital Recovery Factor (CRF)[1] for the interest rate and period. In this case, the CRF = 0.12130, and the Equivalent Uniform Annual Payment is $321,049.

If the equipment was considered to have a salvage value at the end of its useful life, the amount should be adjusted appropriately and deducted from the expenditures.

Finally, sensitivity analyses should be performed. Sensitivities could include the cost of money, the cost of energy to operate the system, the cost of commercial oxygen, the size of the system (number of diffusers, etc.), or the frequency of major maintenance items. For example, in the above example, compressor overhauls were expected every 10-years. If the overhaul period was changed to once every 8-years and the calculations were repeated, the result would be a Present Worth of $2,649,027, a negligible difference. However, if annual energy costs could be reduced by 20%, the overall Present Worth of the technique would be reduced by $222,588, an appreciable 8%.

Thus, comparing sensitivities within a system allows upper and lower cost boundaries to be established. The range of these boundaries can then be compared from one technique to another to more accurately determine the most economic system.

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[1]The Capital Recovery Factor is often abbreviated as A/P in economic texts.

Appendix G

FUNDAMENTAL ASPECTS OF AIR, OXYGEN, AND NITROGEN

This section is meant to provide the data and information required to estimate the size and cost of the various aeration techniques. It is divided into two areas: the factors involved in deciding whether to use air or pure oxygen to enhance discharge DO levels, and the physical attributes of air, oxygen, and nitrogen.

Considerable license has been taken to simplify the sizing of air flows, compressors, and associated piping. However, these deviations from rigid engineering design procedures should not drastically affect the overall result of the estimating procedure.

G.1 THE CHOICE: AIR OR PURE OXYGEN

Although oxygen can be produced in a number of ways, the only practical sources for hydroelectric applications are either air or pure oxygen that has been delivered or produced on-site. Three fundamental areas should be considered when deciding whether to use air or pure oxygen. These are adverse effects, safety, and cost expenditures.

Adverse Effects

Supersaturation. Supersaturation occurs when the gas is at a higher concentration in solution than when it is in equilibrium with air at ambient temperature and pressure. Low levels of oxygen supersaturation are generally thought safe for aquatic habitat, but levels of dissolved nitrogen even slightly above saturation can cause stress in fish and even become toxic. The procedures to measure total dissolved gas pressure and determine the partial pressure of nitrogen are contained in Standard Methods for the Examination of Water and Wastewater (Ref. G-1).

Because the level of gas saturation is inversely dependant upon the temperature and directly dependant upon the pressure, extreme caution should be taken whenever air is used as the oxygen source to supplement hydropower discharges. Although desired oxygen levels may be achieved by injecting air into the high pressure/cool temperature environment of the hypolimnion, the discharge can quickly become nitrogen-supersaturated when warmer temperatures and reduced pressures are encountered downstream.

For example, in a German reservoir using a Bernhardt (Ref. G-2) hypolimnion aeration system, air was injected into the water column. In a 25-meter rise, 5 mg/L DO was absorbed into the oxygen deficient hypolimnion water. However, 8.4 mg/L of dissolved nitrogen were simultaneously absorbed (which was already 100% saturated in relation to ambient conditions) resulting in 160% dissolved nitrogen saturation.

Due to the strong possibility of supersaturation occurring if air is used as an oxygen source for hydropower aeration systems, it is not recommended for techniques applied upstream of the generator, and should always be closely scrutinized when applied downstream. A suggested procedure is described in the Working Example found in Section 6.1 Tailrace Aeration Techniques / Tailrace Gas Injection / Submerged Diffusers.

Corrosion. As nitrogen supersaturation is a concern when using air, corrosion may be a potential concern in oxygen injection systems. Since no known quantitative tests have been conducted to date, this discussion can only warn of the possibility that accelerated corrosion may occur with pure oxygen injection systems. When turbine venting was applied by TVA at Norris Dam, using air as the source of oxygen, considerable additional cavitiation was encountered. It is hypothesized that if gaseous oxygen were substituted, the corrosion would be even greater. One way to avoid the problem is to be certain that all oxygen is in solution before encountering powerhouse equipment.

Safety

Most people do not fully understand the properties of pure oxygen. The following quote should help to clarify the subject. "The outstanding property of oxygen is its ability to sustain life and to support combustion. Although oxygen is non-flammable, materials which normally will not burn in air may burn in an oxygen rich atmosphere. Materials which burn in air will burn more vigorously and at a higher temperature in an oxygen rich atmosphere. Some combustibles, such as oil, burn in oxygen with near explosive violence if ignited by flame, impact, or other energy source. As a result, caution should be exercised and special precautions taken when entering areas or confined spaces where an oxygen rich atmosphere may exist." (Ref. G-3)

Oxygen storage and distribution systems should only be designed by qualified engineers. Liquid oxygen will cause severe burns if in contact with the skin for only seconds. Liquid oxygen tanks must be located to allow for safe venting of excess pressures. Piping velocities are also critical. Because of the inherent hazards, many reference standards exist, particularly from the American National Standards Institute (ANSI). Some of these are ANSI B31.1 "Chemical Plant and Petroleum Piping"; ANSI B31.8 "Gas Transmission and Distribution Piping Systems", and ANSI B31 Code Case #75 "Piping For Gases, Including Air". The American Petroleum Institute (API) provides API Standard 1104, "Standard for Welding Pipelines and Related Facilities", and the National Fire Protection Association (NFPA) has NFPA 51 "Oxygen Fuel Gas Systems for Welding and Cutting".

One advantage of oxygen when applied to hydropower discharges is that the velocities and pressures of the gas are generally well below dangerous levels. Internal pressures less than 200 PSI and velocities less than 100 ft/sec are well below the maximum allowable levels for steel pipeline systems, as indicated in Figure G-1 (Ref. G-4). However, it should be pointed out that velocities will increase at flow restrictions such as valves, regulators, and branch-line takeoff points. Once again, qualified engineers should be utilized for the design. If high pressures or velocities are encountered, the system must be made from copper-alloy materials.

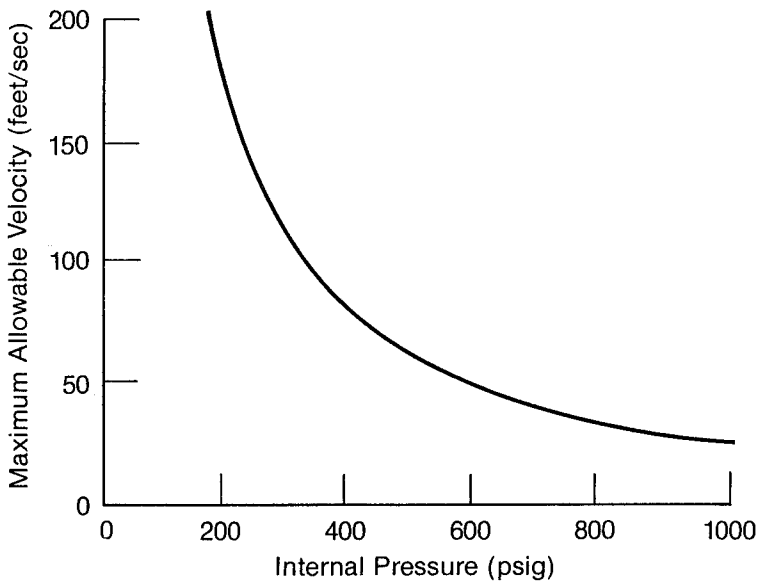


Figure G-1. Maximum safe velocity of oxygen versus internal pressure for steel piping systems; maximum gas temperature: 200°F. (Ref. G-4)

Proper operation of oxygen systems is also important. Rapid filling of an oxygen line from one pressure level to another will result in a temperature increase of the gas within the line due to adiabatic compression. Lines should be pressurized slowly to minimize the temperature rise.

Because oxygen supports combustion, it is essential that the system be free of all dirt, grease, oils, water, filings, scale, weld spatter, and other foreign matter. A detailed cleaning procedure should be specified and followed throughout the project. Cleaning services are also available from consultants within the air separation industry or pipeline cleaning industry (Ref. G-4). Systems that are clean but remain out of service should be pressurized with clean, dry, oil-free nitrogen to prevent condensation from forming.

New piping systems are often tested for leaks using leak test solutions. After these solutions dry, the remaining residue is flammable and therefore becomes hazardous when testing oxygen systems. The hazard can be eliminated by thoroughly rinsing all test surfaces with water after application.

For additional information, two highly recommended publications are provided by the Compressed Gas Association (CGA): "Oxygen" (Pamphlet G-4) (Ref. G-3) and "Industrial Practices For Gaseous Oxygen Transmission And Distribution Piping Systems" (Pamphlet G-4.4) (Ref. G-4). The CGA can be contacted at:

Compressed Gas Association, Inc.
1235 Jefferson Davis Highway
Arlington, VA 22202

Cost Expenditures

The total cost of oxygen supplementation, whether using air or pure oxygen, is based upon three components: the cost of the initial installation, the cost of operating and maintaining the equipment, and the cost of the oxygen. As previously pointed out in the discussion regarding supersaturation, the only occasion when pure oxygen should be directly compared to air is when low pressures are involved, such as with tailrace diffuser systems.

Initial Installation Costs. Systems that rely on air as a source of oxygen enjoy the fact that the gas is free. However, because air only contains 21% oxygen, all of the injection equipment, including the conduits used to transmit the gas, must be 5-times larger than if pure oxygen were used. In addition, although the air may be free, with the single exception of naturally aspirating turbine aeration systems, equipment is needed to compress the air. Compressors require capital expenditure for procurement, installation, and operation. Commercially purchased oxygen (LOX) is pressurized when it arrives at the site, and does not require additional equipment other than vaporizers, which are usually leased from the manufacturer.

Operational and Maintenance Costs. Because the overall amount of equipment is reduced when pure oxygen is used in lieu of air, opera-

tions and maintenance are similarly reduced. This is particularly true when compressors can be avoided as part of the design.

The Cost of Pure Oxygen. One of the major problems contributing to the uncertainty of predicting oxygen costs at a particular site lies in the complexity of the price structure. Not that the production costs of oxygen are that complex, but the market factors strongly control the price. Bulk oxygen plants also produce nitrogen and vice versa. In some cases an air separation plant is built to supply liquid nitrogen for a local industry and there is no demand for the oxygen, so it may have to be wasted back to the atmosphere. In other cases, a plant may be built to supply oxygen to a steel mill and there is no excess capacity for other potential oxygen users. The price of oxygen may vary perhaps threefold under these two market scenarios. The length of the oxygen supply contract will likewise bear heavily on the negotiated price of oxygen.

Pure oxygen can be provided by commercial vendors (liquid oxygen, LOX), or produced on-site using either a cryogenic plant or by the pressure-swing-absorption (PSA) technique. The final selection is based upon amount used, daily/seasonal demand, geographic location, and the desired amount of involvement (or control) the owner wishes to maintain.

Commercial Vendors:
Bulk oxygen production plants are strategically located throughout the United States, usually near industrial centers. The industrial demand for oxygen and nitrogen is supplied by trucking the gas in liquid form to the site, where it is stored in an insulated vessel. The liquid is then passed through a vaporizer where the pressure is reduced and it is gasified for use. The vaporizer can be heated by air, electricity or water. At a hydropower site, a water heat exchanger would seem logical for the vaporizer, resulting in a much smaller installation compared to an air vaporizer, but water pumping equipment would be required and additional operating cost would be incurred. If the tank is not being used to supply gas to the system, oxygen stored as a liquid will escape from the storage container at approximately 0.25% of the remaining liquid per day (Ref. G-5).

Storage tanks and vaporizers may be purchased or leased from the supplier. Because the supplier assumes all maintenance responsibilities, leasing the equipment is usually more economical.

Sizing of the equipment depends not only on the volume of gas required, but also on the distance from the plant. The high variation in daily/seasonal demand of hydroplant discharge aeration applications is a disadvantage of commercially supplied oxygen. Vendors size their plants and plan their production based on a year-round demand. Hydroplants will require sizeable volumes during the late summer months when reservoirs are stratified, but require no oxygen during nonstratified periods of the year. Commercial vendors must pay to have the plant capacity available throughout the entire year, and must charge accordingly. Typically, hydroplant owners will get the best price by negotiating yearly contracts with a number of suppliers. At the Richard B. Russell installation, the cost of oxygen dropped from an initial cost of $86/ton to $43/ton over the first three years, even though overall consumption steadily dropped from 14,000 tons the first year to 7,850 tons three years later. Market competition is attributed as the main reason for the price decrease.

One advantage of the hydroplants' seasonal demand is that it occurs in the summer, when roadways are not likely to be closed due to inclement weather conditions. This allows storage facilities to be sized with a smaller "safety" factor, but does not eliminate the possibility of a shortage of oxygen for other delays such as labor strikes.

Although costs are site-specific and depend heavily on local competition and negotiation, the trucking costs for LOX are nominally less than $5 per ton if the hydropower dam is within a 100 mile radius of the bulk production plant. For transport distances of 100 to 200 miles, the cost would be nominally $10 per ton. Trucks are capable of transporting 20 to 50 tons of liquid oxygen per load.

As an example of typical costs, Minnesota Valley Engineering in New Prague, Minnesota, manufactures cryogenic vessels for storage of LOX.

The 1989 cost for these tanks, not including site preparation and installation, is as follows:

525 gal. (2.5 tons LOX):	$15,250
9,000 gal. (43 tons LOX):	$99,800
11,000 gal. (53 tons LOX):	$116,720

The monthly rental charge for an 11,000 gallon cryogenic vessel for LOX storage is approximately $1,200 per month. (The vaporizing system is included in this rental fee.) The Present Worth of a series of $1,200 monthly payments for 30-years at 12% interest is $115,992. The owner would be responsible for site preparation, but would be free of any maintenance responsibilities. Based on the economics and barring any extenuating site-specific circumstances, owners are recommended to lease LOX storage and vaporization equipment.

Finally, to allow a basic cost comparison with on-site generation systems, if a 40-ton/day system is operated 5-months of the year, the following costs would be incurred:

Oxygen ($75/ton):	$450,000
LOX rental:	28,800
Total annual cost:	$478,800

(Note: the 11,000 gallon tank will normally hold 53 tons of oxygen. To provide a two-day supply, two tanks will be required.)

Assuming an initial installation cost of $25,000 and the life expectancy of the system to be 30-years, the total Present Worth is estimated to be $3,881,734, or $481,878 annually at 12% interest. The overall average price per ton of oxygen is $80.

Cryogenic Oxygen Production:

Cryogenic oxygen production is based upon the fact that once air is liquified, the components have different boiling points and can be taken off as relatively high purity products at the respective points in the distillation tower. Large bulk oxygen and nitrogen plants commonly use cryogenic separation. The energy consumption in these

plants to produce gaseous oxygen is approximately 450 kw-hr/ton, and about twice that amount to produce liquid oxygen for storage (Ref. G-6). (It is not practical to store large volumes of oxygen as a gas.) Because of the high cost of equipment, economy of scale limits the minimum size of a cryogenic plant to 25-40 tons/day.

From Schohl, et al., (Ref. G-7), the cost of installing and operating a cryogenic plant can be estimated using the following equations:

For a plant producing "X" tons/day,

Cryogenic equipment costs:	$\$171,000*X^{0.6}$
Compression equipment:	$20,000*X^{0.6}$
Installation:	$13,500*X^{0.6}$

Additional annual costs for the plant would include:

Insurance:	0.024 * Plant Cost
Maintenance & Repair:	0.04 * Plant Cost
Labor:	Approx. \$1,000 * X
Electricity (annual):	450 * X * (Cost/kWh) * Number of days operated/year

(Note: the figures used for Labor and Electricity are not those presented by Schohl, but are representative of typical installations.)

Because Schohl's estimates are based upon 1976 cost figures, a correction factor for inflation should be applied. Means Building Construction Cost Data 1989 (Ref. G-8) advises that a factor of 1.93 should be used to update the costs from 1976 to 1989. Thus, in 1989 dollars, the capital costs of a 40-ton/day cryogenic plant would be \$3,609,829. The annual cost of insurance would be \$86,636. Under the assumption that the plant is operated at full capacity for a 5-month period, then shut down for the balance of the year, maintenance costs would be \$144,393/5= \$28,879; labor costs would be \$40,000/5 = \$8,000; and electricity (\$0.06/kWh) would cost \$162,000. The total annual cost is \$285,515.

To take full advantage of the crogenic process, additional energy costs should be included to produce liquid oxygen, along with a LOX storage facility.

If a 30-year life is assumed, the annual costs are converted to a single Present Worth value, the total Present Worth of the above cryogenic system is $5,909,652, or $733,663 annually at 12% interest. This equates to an overall average of $122/ton of oxygen produced.

PSA Oxygen Production Plant:
The second approach for on-site oxygen production is pressure swing adsorption (PSA) using molecular sieve beds. The technique involves a zeolite bed that, when pressurized, will absorb nitrogen from air. When the zeolite bed is under pressure, it selectively retains the gaseous nitrogen component of the air, allowing an oxygen enriched product to result. When the bed capacity becomes saturated with respect to retaining additional nitrogen, it can be regenerated by simply reducing the pressure to atmospheric, and the nitrogen is released from the bed. The oxygen product can be economically regulated to 80-95% purity.

An advantage of PSA systems is that they can be easily modularized. Packaged systems are capable of producing 20 to 80,000 pounds per day. The systems have been used for many years in auto body shops for oxygen production for cutting torches and in hospitals. In the past few years, there has been an increasing number of installations in aquaculture for fish production, and in steel production facilities.

The longevity of PSA systems is also good. Other than the air compressors, the only moving component is the valve used to control bed pressure. Provided the air filters for removal of hydrocarbon gases are maintained, bed life has been known to last for at least 10-years.

The nominal cost of a molecular sieve PSA system that produces 1-ton of oxygen per day is $40,000. A system capable of providing 40-tons/day is approximately $1,200,000.

The energy consumption of the larger plants is about 430 kWh/ton of oxygen at 90% purity, delivered at a pressure of 200 PSIG. Using the same formula as for the cryogenic plant, annual insurance for the 40-ton/day plant would be $48,000. Maintenance would consist of valve seat replacement, compressor repair, and periodic painting, for approximately $10,000 annually. The plants are fully automatic and not labor intensive; the manufacturers suggest the equipment be checked once or twice a day as a precaution. For a 150-day operating season, this would amount to approximately $4,500. Electrical costs ($0.06/kWh) for the same period would be $154,800.

If the annual costs are converted to a single Present Worth value, a 30-year life is assumed, and the total Present Worth of the above PSA system is $2,950,352, or $366,276 annually at 12% interest. This equates to an overall average of $61/ton of oxygen produced.

Combination of On-Site Generation and Commercially Supplied Oxygen: The above discussions must be compared very carefully. The LOX system is based upon a purchase price of $75/ton. This rate is highly variable, and will certainly make a major difference in the overall economic analysis. Both the cryogenic and PSA systems are analyzed using an electrical rate of $0.06/kWh. Again, the value of this figure may vary, depending upon the site-specific situation, and have a very strong influence on the overall economic analyses.

The above calculations assumed a simplified oxygen-demand rate of 40 tons/day. However, the nature of the oxygen demand pattern for hydroelectric oxygen supplementation is variable. Oxygen demand may begin at a low rate in perhaps May or June, peak in August or Septem-

ber, and cease altogether with Fall turnover in October or November. Within this seasonal variation, peaking powerplants will experience both daily and weekly variations in which no water may be discharged on Saturday and/or Sunday.

Unless the rate of oxygen production can be matched to the demand, on-site storage will be required. At Richard B. Russell Dam on the Savannah River, continuous, round-the-clock oxygen injection is provided to minimize the need of on-site storage and the size of the oxygen dissolution equipment. The reservoir serves as an effective storage device and can eliminate or at least minimize the need for storage of on-site oxygen.

The most economical scheme will often favor a combination of on-site production for a fraction of the oxygen demand, with the remainder supplied commercially. Early in the year, the commercial supply would be used to meet the small demand of early stratification, with the on-site system used once it can be operated continuously. This scheme allows for a smaller on-site production plant, and a shorter period of operation, resulting in a longer period to amortize the initial capital investment.

G.2 PHYSICAL ATTRIBUTES OF AIR, OXYGEN, AND NITROGEN

The physical attributes of air and its constituent gases can be very complex. Its behavior is influenced by a number of factors, including pressure, temperature, water vapor composition, barometric pressure, and elevation. An excellent presentation of how these factors interact and their relevance in both freshwater and saltwater systems has been made by Colt (Ref. G-9), and is a recommended source for in-depth investigations. However, for the fundamental estimating procedures outlined in this manual, the following material may be sufficient.

Standard Conditions

One aspect that quickly becomes obvious when working with numerous sources of data involving air or its constituent gases is that all numbers are related to "standard conditions". Depending upon the

source of the data, however, "standard conditions" can vary. In fact, there are probably more than a dozen different "standard conditions". For example, the compressor industry often uses a standard condition of 14.7 PSIA and 70°F. The gas supply industry will use 14.696 PSIA and 60°F, and the ASME defines standard conditions as 14.70 PSIA, 68°F (20°C), and a relative humidity of 36%. Others use standard conditions that are considerably different.

Whether these differences have a substantial impact in estimating the costs associated with aeration techniques depends upon the application. For the majority of situations, the differences will be insignificant. The point to remember is that standard conditions are not universal.

Density of Air

The density of air changes with both pressure and temperature. "Standard" barometric pressure is considered to be 14.696 PSIA (29.92 inches-Hg) at sea level. Because various aeration techniques use air as a source of oxygen, the density of air must be known at elevations other than sea level, and at conditions other than "standard". The following equation can be used to calculate the actual density of the air, if the ambient barometric pressure is known:

$$\rho = \frac{1.325 \times BP}{T + 460} \qquad \text{(G-1)}$$

where:

ρ = Density of air (pounds/ft^3)
BP = Ambient barometric pressure (inches-Hg)
T = Temperature (°F)

If the barometric pressure is known at some nearby location, the pressure at the facility can be calculated using the following equation:

$$\log_{10}(BP) = \log_{10}(BP_R) - \frac{(H - H_R)}{((122.8 \times F) + 56{,}422)} \qquad \text{(G-2)}$$

where:

BP = Ambient barometric pressure (inches-Hg)
BP_R = Reference barometric pressure (inches-Hg)
H = Elevation of facility (feet)
H_R = Elevation of reference location (feet)
F = The mean temperature between the facility and the reference location (°F)

Because the estimates are preliminary and do not require a high degree of accuracy, Table G-1 can also be used to account for the affects of elevation. The Correction Factors can be used to multiply the barometric pressure at sea level to obtain the ambient barometric pressure at the corresponding elevation, provided the temperatures at both locations are approximately the same. It can be surmised from Table G-1 that the effect of elevation is not particularly important unless the facility is located more than 1,500 feet above sea level, in which case an error greater than 5% would be introduced. As the estimating process is worked through, it will be discovered that errors less than 5% are not particularly significant.

ACFM Versus SCFM. Some confusion may exist as to the usage of the terms ACFM (Actual Cubic Feet per Minute) and SCFM (Standard Cubic Feet per Minute). As the above discussion indicates, the density of a compressible gas changes with variations in both pressure and temperature. The density of air or oxygen will change when compressed or heated, in the following manner:

$$\frac{P \times 144}{K\,(T + 460)} = \rho \qquad \text{(G-3)}$$

where:

P = Pressure (PSIA)
T = Temperature (°F)
K = A constant; K = 53 for air;
K = 48.23 for oxygen
ρ = Density (lbs/ft^3)

Table G-1

ELEVATION CORRECTION FACTORS

Feet Above Sea Level	Correction Factor
0 - 1,000	1.000
1,000 - 1,500	0.950
1,500 - 2,000	0.932
2,000 - 2,500	0.915
2,500 - 3,000	0.897
3,000 - 3,500	0.879
3,500 - 4,000	0.862
4,000 - 4,500	0.844
4,500 - 5,000	0.826
5,000 - 5,500	0.809
5,500 - 6,000	0.791
6,000 - 6,500	0.773
6,500 - 7,000	0.756

Source: Ref. G-10 (Aeration Industries)

The quantities of ACFM and SCFM can be conservatively related using the following isothermal relationship:

$$P_S \times V_S = P_A \times V_A \qquad \text{(G-4)}$$

where:

P_S = Pressure under standard conditions (PSIA)
V_S = Volumetric flowrate under standard conditions (SCFM)
P_A = Pressure of compressed gas (PSIA)
V_A = Volumetric flowrate of gas under compressed conditions (ACFM)

It must be reiterated that the above equation should only be used for fundamental estimating purposes.

It is interesting to note that in applications using submerged diffusers, it is the practice of at least TVA to base the number of diffusers on only the SCFM volume, and ignore the ACFM volume. This

results in more diffusers being specified, with a considerably smaller supply rate per unit. Without better diffuser performance data, this practice is recommended for others designing submerged diffuser systems. The added cost for the additional diffusers is usually only a very small percentage of the total cost of the application, and the added number of diffusers helps assure that the system will perform satisfactorily.

Estimating Compressor Horsepower

Thermodynamics dictate that air is compressed in either of two ways: adiabatically or isothermally. Adiabatic expansion or compression occurs when air is expanded or compressed without the transmission of heat to or from it. For example, adiabatic compression would occur if air were compressed in a totally-insulated, non-conducting cylinder. Isothermal expansion or compression takes place when the gas is expanded or compressed with an addition or loss of sufficient heat to maintain a constant temperature. (Ref. G-11)

For adiabatic compression:

$$\text{Total foot-pounds of work} = 3.46\ P_1\ V_1 \left[\left(\frac{P_2}{P_1} \right)^{0.29} - 1 \right] \qquad \text{(G-5)}$$

and, for isothermal compression:

$$\text{Total foot-pounds of work} = P_1\ V_1\ \log_e \frac{V_1}{V_2} \qquad \text{(G-6)}$$

where:

P_1 = Initial absolute pressure in pounds/ft^2 (PSFA)
P_2 = Final absolute pressure in pounds/ft^2 (PSFA)
V_1 = Initial volume in ft^3
V_2 = Final volume

In reality, the actual amount of work to compress air is an average of these two values. To estimate the average amount of horsepower required, the above equations can be used to determine the average amount of foot-pounds per minute, and then multiplied by a conversion factor of 3.03×10^{-5}. Table G-2 presents the estimated horsepower to compress 100 CFM of air if the initial pressure is 14.7 PSIA and the compressor efficiency is 65%.

Table G-2

APPROXIMATE COMPRESSION HORSEPOWER
(Initial pressure = 14.7 PSIA, 65% Compressor efficiency)

PSIG	HP/100 CFM	PSIG	HP/100 CFM
5	2.97	55	18.00
10	5.38	60	18.77
15	7.38	65	19.69
20	9.23	70	20.46
25	10.77	75	21.23
30	12.15	80	22.00
35	13.54	85	22.77
40	14.77	90	23.38
45	15.85	95	24.15
50	16.92	100	24.77

Saturation Concentrations

The saturation concentration for oxygen and nitrogen at different temperatures and 1-atmosphere of pressure are tabulated in Table G-3.

The saturation concentrations, C^*, at pressures other than 760 mm-Hg can be calculated using the following equation:

$$C^* = C^*_{760} \frac{(P_t - P_{VP})}{(760 - P_{VP})} \qquad (G-7)$$

Table G-3

SOLUBILITY OF OXYGEN AND NITROGEN, AND WATER VAPOR VARIATIONS BOTH TEMPERATURE

(Barometric pressure = 29.92 inches-Hg, 760 mm-Hg)

T, °C	O_2, mg/L	N_2, mg/L	Water Vapor Pressure (mm-Hg)
0	14.602	23.04	4.58
1	14.198	22.45	4.93
2	13.813	21.88	5.29
3	13.445	21.34	5.68
4	13.094	20.82	6.10
5	12.757	20.33	6.54
6	12.436	19.85	7.01
7	12.127	19.40	7.51
8	11.832	18.96	8.05
9	11.549	18.54	8.61
10	11.277	18.14	9.21
11	11.016	17.76	9.85
12	10.766	17.39	10.52
13	10.525	17.03	11.23
14	10.294	16.69	11.99
15	10.072	16.36	12.79
16	9.858	16.04	13.64
17	9.651	15.73	14.53
18	9.453	15.44	15.48
19	9.261	15.15	16.48
20	9.077	14.88	17.54
21	8.898	14.61	18.66
22	8.726	14.36	19.83
23	8.560	14.11	21.08
24	8.400	13.87	22.39
25	8.244	13.64	23.77
26	8.094	13.41	25.22
27	7.949	13.20	26.75
28	7.808	12.99	28.36
29	7.671	12.78	30.06
30	7.539	12.58	31.84
31	7.411	12.39	33.71
32	7.287	12.21	35.68
33	7.166	12.02	37.75
34	7.049	11.85	39.92
35	6.935	11.68	42.20
36	6.824	11.51	44.59
37	6.716	11.35	47.10
38	6.612	11.19	49.72
39	6.509	11.04	52.48
40	6.410	10.89	55.36

Adapted from Colt (Ref. G-9)

where:

C^* = Saturation concentration (mg/L)
C^*_{760} = Saturation concentration at 760 mm-Hg pressure (mg/L)
P_t = New barometric pressure (mm-Hg)
VP = Water vapor pressure from Table G-3 (mm-Hg)

The Effect of Depth

Hydrostatic pressure increases the solubility of gases. Colt (Ref. G-9) states that the solubility of gas doubles with approximately every 10-meters of depth, and presents the following relationship:

$$C_Z = C^* \times \left[1 + \left(\frac{Z}{10.35}\right)\right]$$

where:

C_Z = Saturation level at depth Z
C^* = Saturation level at atmospheric pressure
Z = Depth (meters)

Because gas solubility increases with depth, hydroplant discharges can be supersaturated. Water under pressure can contain more gas than when exposed to the atmosphere, yet not be supersaturated. When the water passes through the turbine and is discharged, the acting pressure is reduced, but the mass of gas contained in the water is conserved. Thus, the water becomes supersaturated until equilibrium is reached with the new ambient pressures downstream of the project.

The total pressure, P_t, at depth H is equal to:

$$P_t = P_{Atmospheric} + P_{Hydrostatic} = BP + \rho\ g\ H$$

where:

P_t = Total pressure (lbs/ft^2)
BP = Barometric pressure (lbs/ft^2)
ρ = Density of water (lbs/ft^3)
g = Acceleration of gravity (32.2 ft/sec^2)
H = Depth (ft)

Knowing P_t, the saturation value at any depth, C^*_H, can be calculated using Equation G-7.

Estimating Pipe Size

Many of the aeration techniques require pipes to supply air or oxygen to the water. To estimate the cost of these projects, the approximate size and quantities of materials must be determined. For estimating purposes only, the following equation may be used to determine the diameter of the pipe and fittings:

$$d = \left(\frac{Q^2 \rho L}{3,364 P} \right)^{1/5} \qquad \text{(G-8)}$$

where:

d = Pipe diameter (inches)
Q = Gas flow (ACFM)
ρ = Density of the entering gas (lbs/ft^3)
L = Equivalent length of pipe (feet)
P = Pressure drop in pipe (PSI)

The flow, Q, must be in Actual Cubic Feet per Minute, and can be estimated using Equation (G-4). The density, ρ, can be calculated using Equation (G-3). The length of equivalent pipe is determined by adding the total lineal feet of pipe to "equivalent lengths" of pipe that represent the frictional losses through each of the various fittings. Adding approximately 25% to the lineal length will suffice for estimating purposes. The pressure drop can be adjusted to balance pipe size with required supply pressure. The larger the pipe size, the smaller the compressor and operating costs. However, large diameter pipe is expensive, so a compromise is needed. Remember, every time the pressure drop is changed, the supply pressure changes, and the density must be recalculated.

As an example of using Equation (G-8), assume that 19,800 SCFM must be delivered to diffusers 800-feet away. The air will be injected at a depth of 20-feet. The air temperature is 70°F.

The 20-feet of head is approximately equivalent to 9.0 PSIG. Since the flow is large (19,800 SCFM), assume a rather large frictional loss in the supply header to minimize the diameter; assume a frictional headloss of 15 PSI. Therefore, the supply pressure must be 15 + 9 + 14.7 = 38.7 PSIA. The ACFM for the system is calculated using Equation (G-4), and is 7,521 ACFM. Using Equation (G-3), the density is 0.20 lb/ft^3. The equivalent length of pipe is 800 x 1.25 = 1,000 feet. Substituting into Equation (G-8):

$$d = \left(\frac{(7,521)^2 \ (0.2) \ (1,000)}{(3,364) \ (15)} \right)^{1/5} = 11.75$$

Therefore, a nominal 12-inch diameter pipe would serve as a supply header.

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