# REPORT TO CONGRESS
# DAM WATER QUALITY STUDY

Prepared by:

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# EXECUTIVE SUMMARY

The objective of this report is to identify water quality effects attributable to the impoundment of water by dams as required by Section 524 of the Water Quality Act of 1987. This document presents a study of water quality effects associated with impoundments in the U.S.A.

This Executive Summary provides the general observations of the report followed by summaries of each of the six major report elements. First, a generic description of water quality effects of dams based on existing knowledge is presented. Four types of analyses are then used to attempt to define the occurrence and magnitude of water quality effects within and downstream of impoundments: a mixing analysis; an analysis of dissolved oxygen concentrations in power dam tailwaters; a comparison of upstream versus downstream concentrations of selected indicator parameters; and an investigation of phosphorous enrichment. Case studies are presented to illustrate some of the water quality effects and mitigation measures. Next, a generic discussion of mitigation measures for addressing some of the water quality effects is presented. Assessments of water quality conditions at U.S. Army Corps of Engineers, Tennessee Valley Authority, and the U.S. Bureau of Reclamation impoundments are provided as a supplement to these analyses. Finally, conclusions on impoundment effects on water quality are presented.

There are a large number of dams throughout the United States. The Soil Conservation Service estimates there are over 2,000,000 dams including farm ponds and recreational impoundments. The Corps of Engineers (U.S. Army Corps of Engineers, 1982b) inventoried 68,155 larger dams meeting minimum size criteria. These 68,155 dams are the basis of the Environmental Protection Agency (EPA) analyses in this study. They can be divided into three categories: large power dams (424), large nonpower dams (1,701), and small dams (66,030). The large power dams contain 62 percent of the total volume of water normally stored by dams; large nonpower and small dams contain 33 and 5 percent of the total volume, respectively. Dams have a variety of purposes which include hydropower generation (including pump storage), navigation, flood control, water supply, conservation, recreation, fish and wildlife maintenance, and low flow augmentation.

This study is limited in estimating the national extent of dam water quality primarily because of a lack of monitoring and descriptive data. The **STO**rage and **RET**rieval data base (STORET) was used as the primary source of monitoring data. Although quite extensive, data were not available for many of the sites randomly selected for analysis. Other descriptive data, such as the type of outlet structure, watershed land use, and other influences on water quality, were also not available for this study. Additional monitoring data, descriptive data, and a larger random sample of dams would probably extend the study's findings. This study is also limited in that it identifies water quality effects from the impoundment of waters by dams, but does not address the effects on biological habitat or wetlands, which may be substantial.

## WATER QUALITY EFFECTS OF IMPOUNDMENTS

Impoundment of free-flowing water by dams may potentially create several effects, both positive and negative, on water quality within the pool and downstream. Although this report focuses on unwanted effects, desirable changes, such as a reduced sediment load, may also result. The potential effects are often interdependent. Altering one condition in an impoundment may create a ripple of effects throughout the reservoir-stream ecosystem.

Impoundments can modify the physical, chemical, and biological characteristics of the free-flowing aquatic ecosystem. Physical and chemical characteristics in impoundments are also related to depth, volume, climate, watershed land use, geographic location, reservoir siting, and the schedule of water releases. Biological characteristics are related to the type of habitat. The magnitude of effect of the dam on water quality of releases appears related to the type of reservoir and to the design and operation of the impoundment.

Effects can be divided into three categories: stratification-related effects, eutrophication, and other changes. Stratification, a naturally occurring condition, results when warmer waters overlie cooler, denser waters. Deeper impoundments with poor mixing tend to stratify. Stratification water quality effects may include:

- low dissolved oxygen in the hypolimnion (bottom waters);
- increased dissolved iron and manganese concentrations;
- hydrogen sulfide production;
- production of nitrous gas; and
- changes in water temperature.

Eutrophication is a naturally occurring process where excess nutrients (especially nitrogen and phosphorus) from watersheds flow into an impoundment. These excess nutrients cause increased and sometimes undesirable growth of algae and rooted plants. This situation, coupled with stratification, may result in the depletion of dissolved oxygen in the bottom layer of the impoundment and the release of soluble iron, soluble manganese, and hydrogen sulfide.

When there are stratification-related effects, possibly compounded with eutrophication, impoundments with outlets accepting withdrawals from lower impoundment depths transmit the water quality of the pool's lower levels into the tailwaters. Large power dams are more likely to have low-level outlets than are small and large nonpower dams because project purposes influence the type of outlet.

Other water quality effects of dams are generally considered to be less predominant than eutrophication and stratification-related effects. Other effects include gaseous supersaturation, salinity changes, sediment deposition, sediment movement, flow regulation, reaeration denial (the restriction of natural reaeration processes), fish entrainment (the capture and passage of fish through turbine machinery), and toxics accumulation. Downstream transport of toxic-bearing sediments from the pool area may occur if sediments are disturbed by dredging, dam removal, or dam failure.

RESULTS OF EPA ANALYSES

Information on small and large nonpower impoundments is limited, and no quantitative conclusions are reached through the analyses of effects of these two categories of dams, with the exception of the mixing analysis for large nonpower impoundments. Data obtained for this study on these two categories are presented in the appendices. Quantitative findings, limited to a few broad conclusions for large power impoundments, are presented below:

> The mixing analysis using Froude numbers indicates that stratification conditions ("poor mixing") are estimated to occur in 40 percent of the large power impoundments and 37 percent in the large nonpower impoundments. The Froude number, which considers only the kinetic and potential energy provided to the flowing waters by gravity, is a limited predictor of stratification. The influence of low-level releases on these results is unknown.
>
> Dissolved oxygen levels in tailwaters in the dams of the Oak Ridge National Laboratory study (Cada, et al., 1983) and the dams in this study are similar. The data are not intended to quantify the dissolved oxygen findings on a national basis, but certain relationships are observed in the sample:
>
> - Dissolved oxygen in power dam tailwaters during the summer has a much greater probability of not meeting a criterion of 5 mg/l than during winter.
>
> - Larger power-generating facilities show greater probability of not meeting a dissolved oxygen criterion than do smaller power-generating facilities.

- Dissolved oxygen in downstream water showed a decrease in 22 to 50 percent of the waters below large power dams, based on a comparison of upstream and downstream dissolved oxygen levels of 40 large power dams. Similarly, 15 percent to 42 percent showed an increase in dissolved oxygen, while 35 percent to 62 percent showed no change.
- Large power impoundments are likely to experience phosphorous enrichment, an indicator of potential eutrophication. The sample for large power impoundments showed such potential in 58 percent to 78 percent of the sample. However, phosphorus enrichment is only one of several factors, including climate and the presence of other nutrients, resulting in eutrophication.

## CASE STUDIES

Case studies provide a detailed examination of several of the water quality effects and mitigation measures presented in this report. The fifteen case studies are not representative of all impoundments in the nation. They do, however, represent impoundments specifically studied because they exhibit, or are thought to exhibit, certain water quality effects. In order to maintain perspective in the discussion of case studies, one of the case studies included is reported to have no undesirable effects. The case studies describe, in most situations, efforts undertaken by operating Agencies to mitigate undesirable water quality conditions within the operating and legal constraints imposed at the time the dams are authorized and constructed. The fourteen case studies showing adverse water quality effects exhibit one or more of the following: low hypolimnetic dissolved oxygen, increased iron and manganese, eutrophication, hydrogen sulfide, sediment movement, flow regulation, thermal changes, and reaeration denial. All of the case studies that exhibit increased iron and manganese, eutrophication, thermal change, and hydrogen sulfide have low hypolimnetic dissolved oxygen. Mitigation measures used to improve water quality in the pool are typically reaeration or destratification by pumping and/or air injection. Mitigation of water quality downstream of the impoundments is typically selective withdrawals and turbine aeration.

## MITIGATION MEASURES

This report identifies major mitigation measures (mainly oriented to addressing tailwater improvements below power dams) that can address the adverse water quality effects associated with certain impoundments. Because each impoundment system is unique, the applicability of specific mitigation measures must be evaluated on a case-by-case basis. This evaluation must consider the adverse effects that require correction, the present impoundment purposes, the measure cost, and the undesirable side effects of the measure itself. Oftentimes, multiple measures may be necessary. Mitigation measures can be divided into three broad categories: physical measures, operational measures, and structural modification.

Physical measures include technologies that require specific processes or equipment to be used to correct the problem. Physical mitigation measures include the control of water quality in the reservoir, selective withdrawal of reservoir water with acceptable water quality, aeration of reservoir releases, and habitat modification.

Operational measures include changes to the present operating regime of the reservoir modification. These include maintaining a minimum discharge, limiting the maximum discharge, and altering the rule curves for reservoir operations.

Structural modifications involve changes to the structure of the dam and/or its outlet works; examples are the addition of ports, gates, vents, or weirs to modify the depth or manner in which water is withdrawn from the reservoir.

Mitigation measures can be applied to the pool, tailwaters, and/or to the sources of runoff to the impoundment. Three pool mitigative measures are induced mixing, aeration of the bottom layer of a stratified impoundment, and dredging applied directly to the impoundment pool. Induced mixing usually is the pumping of surface waters downward or pumping of bottom waters upward, and is intended to reduce stratification effects. Aeration through injection of air or oxygen raises dissolved oxygen concentrations, and may induce mixing. Dredging, the physical removal of sediment deposits, may lengthen the useful life of an impoundment, but may result in short-term water quality problems through the resuspension of nutrients and contaminants.

Three mitigative measures applied to tailwaters are aeration of reservoir releases, selective withdrawal of reservoir water, and improvement of tailwater habitat. Aeration of reservoir releases may be achieved by turbine venting, air injection, and/or cascaded tailwaters. Selective withdrawal is the ability to choose a withdrawal depth with appropriate dissolved oxygen levels and temperatures. Habitat improvement provides minimum flows and D.O. levels required to support target fish populations in downstream pools.

Other mitigative measures involve watershed management and changes in dam operations. Watershed management addresses reducing the nutrient and contaminant sources (nonpoint source pollution) in the watershed of an impoundment. One change in dam operations is to maintain a minimum constant discharge where zero discharge periodically occurs. This helps maintain a minimum flow to avoid rapid temperature fluctuations, reduce the impact of low dissolved oxygen concentrations through natural aeration (unless the minimum release itself has a very low dissolved oxygen concentration), and increase habitats for fish and benthic biota. A second change in dam operation is to limit discharges to a certain maximum flow, reducing impacts on dissolved oxygen during periods of low concentrations in the discharges through natural aeration in the tailwaters.

## FEDERAL AGENCY ASSESSMENTS

The U.S. Army Corps of Engineers (COE), the Tennessee Valley Authority (TVA), and the U.S. Bureau of Reclamation (USBR) provided supplementary information to this report on water quality conditions at their dams. These three agencies requested that they be allowed to contribute specific assessments of the dams they manage. None of the other commenters offered similar assessments. Information provided by each Agency includes:

- Statement of policies and procedures followed by these Agencies in the development and management of water resources.
- Assessment of water quality with respect to the Agency's dams.

Dams managed by these three Agencies represent a broad range of geography, climate, and operational situations. COE dams are typically multipurpose, and may include flood control, navigation, hydropower, water supply, water quality, recreation, and fish and wildlife enhancement. The COE dams are concentrated along mainstem navigable rivers, coastal areas, industrialized areas of the Southeast and the Ohio River Basin, and the Pacific Northwest. These dams contain approximately 34 percent of the total volume of water normally stored by all 68,155 dams. TVA operates reservoirs in the Tennessee Valley primarily for purposes of navigation, flood control, and electrical generation. The TVA reservoirs represent mature reservoirs in a well developed and somewhat industrialized extended river basin. Normal storage volume at TVA reservoirs is approximately 2 percent of the total volume. USBR reservoirs are primarily in the western states, typically in arid areas. The USBR projects are often multipurpose, and include: water supply, hydropower, irrigation, water quality, flood control, river regulation, recreation, and fish and wildlife enhancement. USBR reservoirs, at normal pool volumes, account for approximately 22 percent of the total volume. The remaining 42 percent of normal pool volume is impounded behind dams owned by other governmental entities or privately.

Information for the Agencies' assessments was obtained through a questionnaire designed to collect information on project design, operation, and water quality status. The questionnaires were completed by agency personnel familiar with each dam. Subjective responses were requested in regard to water quality problems of pool waters and tailwaters. Where problems were indicated, the impact of each problem upon user benefits is estimated and a rating assigned. User benefits vary by individual project. Analysis of the results is limited to frequency of occurrence of specific water quality conditions and their impact upon user benefits.

Water quality problems at the Agencies' impoundments vary in frequency and in degree of impact. Overall, physical conditions, such as fluctuating pool and tailwater levels and high and low flows, appear to be the primary conditions affecting user benefits. Data are lacking for many chemical water quality parameters. For the TVA system, chemical concerns are usually more serious than physical concerns, even though the latter are not prevalent. Eutrophication and related water quality conditions (e.g., algae, high nutrient levels, and low dissolved oxygen) are noted in many reservoirs.

The COE survey evaluates 46 of their 700 impoundments. Approximately half of the 46 projects have water quality data. Tailwater problems are identified in 35 to 40 percent of the samples with data. Flow fluctuation and high and low flows are the key problems. Pool water problems in 40 to 50 percent of the samples with data are identified as eutrophication and related problems (high nutrients, low dissolved oxygen, algal blooms, and macrophytes).

The TVA survey evaluates all 33 of their large impoundments. Data were available for dissolved oxygen, temperature, flow, pool levels, and macrophytes at all projects. Data for the other parameters were available for an average of 60 percent of the projects. Tailwaters experienced problems with low dissolved oxygen, flow fluctuations, high and low flows, and low temperature at 40 percent of their dams. Significant pool water problems include level fluctuations at 50 percent of the projects, bacteria at 30 percent, and turbidity, algae, macrophytes, and sediment at 15 to 20 percent.

The USBR survey evaluates 250 of their 349 impoundments (41 percent of the tailwaters and 46 percent of the pool water sampled have water quality data). High flow is the primary problem in tailwaters, affecting 21 percent of those with data. Drawdown and pool level fluctuations are identified as the main impact-producing conditions in reservoir pools, occurring at 36 percent and 35 percent, respectively.

Because of the lack of data on the majority of dams, the questionnaire results do not present a complete picture of water quality for each Agency's impoundments. Also, it is likely that existing water quality data were only collected at projects with known or suspected problems; the resulting picture may, therefore, be skewed toward conditions at which problems are perceived. The data are insufficient to support specific conclusions applicable to all dams; however, preliminary evaluations indicate that although project operation plays a significant role in determining water quality of reservoir releases, there are pronounced regional patterns of water quality conditions associated with dams. Regional attributes, such as geology and climate, together with watershed processes and land use, play a major role in reservoir water quality. The Agencies feel the limited analysis presented herein gives an accurate picture of the known extent of given water quality conditions across a broad range of geography, climate, and project operating criteria, along with an assessment of the perceived impacts of these conditions on user benefits.

**CONCLUSIONS**

The overall conclusions for this study are based on both the agency assessments and the EPA analytical results. Impoundment of free-flowing water by dams may potentially create several effects on water quality. Effects can be divided into three categories: stratification-related effects, eutrophication, and other changes, such as gaseous supersaturation. Dam outlets at low levels transmit the water quality of the pool's lower levels into the tailwaters. Poorly mixed or stratified impoundments with low-level outlets (inhibiting reaeration) are likely to exhibit low levels of dissolved oxygen and increased levels of reduced iron and manganese concentrations in the tailwaters. Furthermore, dams that create impoundments with long detention times have the potential for nutrient enrichment when the upstream runoff includes significant nutrients from point or nonpoint sources. Nutrient-rich impoundment waters are an indicator of potential excessive eutrophication.

The results of the four EPA analyses conducted for this study (mixing, tailwater dissolved oxygen, upstream/downstream comparison of parameters, and phosphorous enrichment) cannot be directly related to the findings of the COE, TVA, and USBR assessments due to differences in analytical methods. However, a few complementary findings are noted:

- A decrease in dissolved oxygen from the upstream to downstream was found in 22 to 50 percent of large power impoundments in the EPA analysis.
- According to the other agency assessments, 20 percent of COE's projects, 38 percent of TVA's projects, and 4 percent of USBR's projects experience low dissolved oxygen in tailwaters.
- Low dissolved oxygen occurs more frequently in eastern dams, particularly in southeastern dams.
- Phosphorous, a potential indicator of eutrophication, occurred at levels above a guidance of 0.025 mg/l in 58 to 78 percent of large power impoundments in the EPA analysis. High nutrient levels (presumably a mix of nitrogen and phosphorous) were reported in 35 percent of COE's pools, 30 percent of TVA's pools, and 15 percent of USBR's pools in the other agency assessments.

The study identifies water quality mitigation methods that can be evaluated on a case-by-case basis:

- induced mixing of the impoundment pool;
- aeration of the bottom layer of a stratified impoundment and aeration of impoundment releases;

- dredging to remove sediment deposits;
- selective withdrawal to provide a choice of withdrawal depth;
- habitat improvement of downstream pools to support desired fish populations;
- watershed management to reduce upstream nutrient and contaminant sources that drain to an impoundment;
- constraining reservoir releases to maintain target minimums or to be less than target maximums.

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# I. INTRODUCTION

## OBJECTIVES AND HISTORICAL CONTEXT

The objective of this document is to fulfill EPA's responsibility to provide a report to Congress on Dam Water Quality in response to Section 524 of the Water Quality Act of 1987. The report addresses the water quality effects associated with impoundments and attempts to estimate the character and national extent of these effects. The specific language of Section 524 is:

**Sec. 524 DAM WATER QUALITY STUDY**

> **"The Administrator, in cooperation with interested States and Federal agencies, shall study and monitor the effects on the quality of navigable waters attributable to the impoundment of water by dams. The results of such study shall be submitted to Congress not later than December 31, 1987."**

The effects of impoundments on water quality has been a topic of interest for many years. At a 1963 symposium on impoundments, W.E. Knight, from the state of North Carolina, summed up the situation (USHEW, 1965):

> "The effects of storage on water quality have been the subject of much study by Federal and State agencies. Thermal stratification of lakes has been recognized by man since he first dived into a lake and found the water near the bottom colder than that at the surface. Likewise, the fact that at times water near [illegible] a reservoir contains little, if any, dissolved oxygen has long been known. Studies of the concentration of dissolved oxygen in water discharged from reservoirs indicate that during the critical summer period, dams with deep intakes discharged water of very low dissolved oxygen content, dams with intermediate intakes discharged water of higher dissolved oxygen content, and dams with high-level intakes discharged water with even higher dissolved oxygen content."

Furthermore, based on 26 years of data, eminent researcher Milo A. Churchill of the Tennessee Valley Authority, concluded (USHEW, 1965):

"If water is released through low-level outlets in the dam, significant effects on downstream water temperature result during the warmer months. If water is released through high-level outlets, the reservoir may have little effect on water temperature".

Thus, it is well known that deep reservoirs thermally stratify and can have poor water quality in their deeper layers. It is also well known that reservoirs retain plant nutrients, nitrogen, and phosphorus and can become eutrophic or filled with excessive aquatic plants from microscopic algae up to, and including, large plants, like water lilies. Unwanted effects can be mitigated, if deemed necessary, in several ways from the aeration of tailwaters for oxygen restoration to the watershed control of nutrients to avoid overfertilization of impoundments.

During the past fifteen years, federal agencies responsible for the planning, construction, operation, and/or regulation of impoundments have taken the initiative and attempted to address many of the emerging water quality issues. In 1978, the Tennessee Valley Authority (TVA) released a report that "identifies adverse impacts on water quality and stream uses that are associated with water releases from dams operated as part of the TVA water management system" (TVA, 1978). TVA identifies several reservoirs as having dissolved oxygen concentrations in their releases that do not constantly attain numerical criteria.

In 1976, the U.S. Army Corps of Engineers (CE) conducted a survey to identify and assess the magnitude of environmental and water quality problems at their reservoir and waterway projects, and to determine major research needs to address these problems (Keeley, et al., 1978). This information was incorporated into a research and development program, Environmental and Water Quality Operational Studies (EWQOS), designed to provide new or improved technology for addressing the environmental and water quality problems associated with these projects, in a manner compatible with authorized project purposes. The EWQOS program represents an eight-year research effort (1977-1985), and included areas such as predictive techniques to help describe, predict, and model various aspects of reservoir hydrodynamics, ecology, and water quality processes. Reservoir operational and management techniques were also developed and evaluated.

The U.S. Bureau of Reclamation has increasingly addressed water quality and other environmental issues for their projects since the late 1960's. Procedures have been pursued for the incorporation of water quality factors in project planning, design, construction, and operations. Supporting research has also been conducted including special programs to address irrigation return flows.

EPA currently addresses water quality issues pertaining to impoundments as part of the nonpoint source program of State and local water quality oversight and area wide management plans. In 1982, the National Wildlife Federation pressed an unsuccessful suit against EPA to regulate dams as point sources rather than continue their regulation under areawide wastewater management plans. All parties to this suit acknowledged various water quality changes brought about by impoundments. What is missing in the transcripts is an estimate of the magnitude of the situation nationally.

This report, with its ramifications, is of interest to the States and Federal agencies that manage impoundments as well as those agencies responsible for regulating impoundments. As requested by Section 524, several States and Federal agencies were solicited for their suggestions and ideas. Federal agencies have also provided case studies to this report to illustrate water quality changes and mitigative methods to counter change at a variety of sites.

With this background in mind, the following questions are addressed in this report:

1. What are the effects of impoundments on water quality?
2. What mitigation measures can reverse unwanted effects?
3. What is the national extent of significant water quality effects?

The answers to questions 1 and 2 are definitive and are supported with case studies. The answers to question 3 are based on elementary statistical tests using limited random sampling and therefore give a preliminary estimate of the national scope of water quality effects associated with impoundments. For some aspects, a national assessment could not be made. More work and analysis are necessary to make these answers definitive.

Section 524 of the Clean Water Act requires EPA to "study and monitor the effects on the quality of navigable waters" due to water impoundment. Thus, the scope of this report is limited to historically documented ambient water quality effects. The report does not address effects on biological habitat or wetlands, which may be substantial. Further, the study is focused on the effects of existing impoundments and does not attempt to assess the water quality or biological effects associated with new impoundments of free-flowing waters in particular geographic areas. Flooding to create new impoundments may cause significant hydrologic changes to the river and destroy wetland and upland habitat, and often raises profound environmental questions. These effects and questions are evaluated by EPA on a site-by-site basis through the Environmental Impact Statement process and as otherwise required by State and Federal law, but are beyond the scope of this report.

## PURPOSES AND NUMBERS OF IMPOUNDMENTS

Impoundments are created for a variety of purposes that provide important social, economic, and aesthetic benefits. Most projects serve multiple purposes. Understanding these purposes is important for providing a context in which to evaluate their water quality consequences. Brief descriptions of the more common purposes are as follows:

- Hydropower Generation - Large hydropower projects tend to have sizable volumes and high dams. Several large TVA projects, though multi-purpose in design and use, have as one of their purposes hydropower generation. However, low head small hydropower projects are more common. There is a current interest in add-on hydropower and this typically is associated with low hydraulic heads. Developers of such projects seek licenses which give them rights of eminent domain and guaranteed markets. Such private development of add-ons to public projects can be a concern to water control agencies because the associated purposes were not included in the original design. Federal and state regulators do review these add-on projects for water quality impacts.

- Pump Storage Hydropower - These projects can be sizable and typically have two water storage pools--a lower pool and an upper pool--with combination turbine/pump(s) between the pools. These combined units are used to balance power generation with power demand. In low demand periods, water is pumped from the lower pool to the upper pool to create potential energy. In high demand periods, the potential energy is converted back to power by release through turbines to the lower pool.

- Navigation - There are numerous navigation projects, having locks, run-of-river dams, and levees. These facilities provide a reliable transportation route for commercial, military, and private transport. Study of polluted navigation pools on the Ohio River, by the Public Health Service nearly 75 years ago, led to the Streeter-Phelps water quality model of dissolved oxygen (Streeter, 1925).

- Flood Control - These projects have a permanent pool which is small in comparison to the large volume set aside to trap floods. A large number of "dry dams" have a very small or no permanent pool.

- Water Supply - Water is stored for public or private use and may include irrigation of agricultural areas.

- Conservation - A large number of small private and public projects are built to maintain ground water levels, trap sediment, control gully erosion, provide livestock watering, and offer recreational activities. The Soil Conservation Service (SCS) frequently assists in the design of these facilities.

- Recreation - Typically, recreation is one use in a multi-purpose federal facility. For example, Corps of Engineers' flood control projects often have a recreational component. In private projects, recreation may constitute the only purpose. Private real estate lakes, like Lake-of-the-Woods, a 500-acre lake that is the centerpiece of a single lot land development in Virginia, are purely recreational.

- Other - Many impoundments service other uses such as fish and wildlife maintenance, water quality enhancement, and low flow augmentation. A combination of these with the above uses is common and play an important role in water resource management.

The development of water resource projects in the public sector follows a procedure that seeks benefits, in terms of achieving stated purposes, in excess of costs. Since passage of the National Environmental Policy Act, this assessment process has explicitly included consideration of environmental consequences. Development of private projects is dependent upon generation of profits to justify their capitalization. Regulated activities in the private sector also are required to satisfy environmental concerns to secure development rights.

In addition to understanding impoundment purposes, an accurate estimate of the preponderance of facilities is necessary to assess national water quality effects. Identifying or counting all of these dams is no small task. To expedite this effort, several existing inventories were evaluated.

The U.S. Army Corps of Engineers compiled an inventory of dams in the United States as part of its National Program of Inspection of Non-Federal Dams (CE, 1982a). This inventory, which was completed in September 1980, includes dams which are in excess of 6 feet in height and have a maximum water impounding capacity of at least 50 acre•feet; or which are at least 25 feet in height and have a maximum water impoundment capacity in excess of 15 acre•feet. The inventory contains 68,155 entries. The Soil Conservation Service (SCS) estimated an additional 2,000,000 small farm pond and recreational dams with volumes less than 50 acre•feet, or dams less than 25 feet high. Approximately 24,000 of entries in the inventory have received technical and/or financial assistance from the Soil Conservation Service. These are the largest of the SCS-assisted dams.

The 68,155 dams in the Corps of Engineers inventory collectively store 490 million acre•feet of water at the normal pool volume. The Corps of Engineers is associated with 166 million acre•feet (34 percent) and the Bureau of Reclamation is associated with 107 million acre•feet (22 percent). The Tennessee Valley Authority is associated with 10 million acre•feet (2 percent).

The Corps of Engineers' listing was chosen as a realistic starting point for a national assessment. Figure I-1 shows the geographical distribution of the dams contained in this 1980 inventory. This listing contains information on hazard potential but also provides the following basic information:

1. Location and name.
2. Volume of impoundment.
3. Maximum depth of water (at the dam).
4. Spillway design flow.
5. Length of dam crest.
6. Power generating capacity (if known and over 100 kW).
7. Purposes.

By itself, this is incomplete information for water quality analysis purposes. But, it provides an exhaustive listing of dams existing in 1980. More complete data for specific dams are available in compendiums of water quality information associated with Corps of Engineers dams. These listings are not exhaustive and are not statistically representative of all impoundments.

## ANALYTICAL DEVELOPMENT

An approach to this nationwide assessment was developed through the comment process as well as a review of the literature. Review of the literature yielded numerous materials on specific case studies, generic problem descriptions, mitigation measures, program reviews, and other elements of the issues surrounding the water quality effects of impoundments. A list of references cited in this report appears in the reference section which includes additional materials reviewed but not cited. Three relatively recent references (TVA, 1978; Cada, et al., 1983; Kennedy and Gaugush, 1987) are representative of alternative approaches to the task at hand. Each tends to be authoritative because of the expertise of the authors and rigor of their methods. All three are sponsored by Federal agencies with a responsibility of some sort for impoundments. The Tennessee Valley Authority owns and operates impoundments. Cada, et al., work for the Oak Ridge National Laboratory (ORNL), which is under the Department of Energy. Finally, Kennedy and Gaugush are with the U.S. Army Corps of Engineers (CE), which manages a large number of dams. The development of the analytical approach for this report to Congress is the result of adapting relevant features of each of these works and making an application to a nationwide assessment.

TVA (1978) adopted a general approach to describing generic effects and mitigation measures while taking a very detailed site-specific examination of many of their reservoirs:

> "Releases from Tennessee Valley reservoirs were evaluated with respect to their adverse impacts on water quality and related characteristics and on various uses of the water downstream. The water quality characteristics examined were temperature,

Alaska - 167
Hawaii - 123
Guam - 1
Puerto Rico - 70
Trust Terr. - 2
Virgin Islands- 8

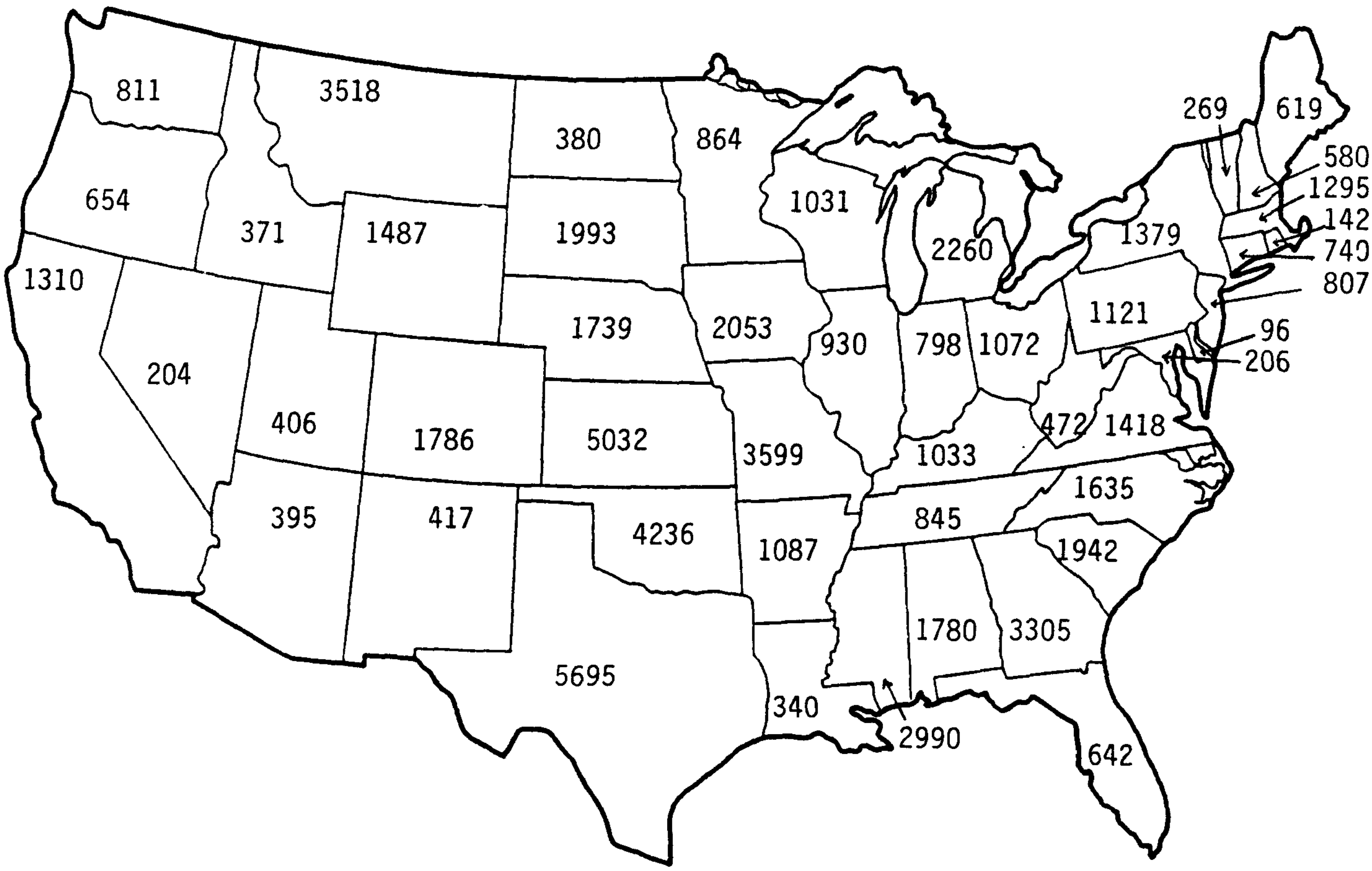



Figure I-1
*Population of 68,155 Dams*
(Source: CE, 1982b)

dissolved oxygen, resolubilization of metals, streamflow, turbidity and suspended solids, and gaseous supersaturation. The downstream water uses examined were recreation, fisheries and other aquatic life, water supply, and assimilative capacity. Evaluations were based on available data on water quality and reservoir operations from 1970 through 1977 in conjunction with biological and engineering judgments of the significance of the impacts."

The TVA study has the following major features:

- Evaluation of a small population of large power-generating impoundments,
- Detailed site-specific analysis of data to estimate effects,
- Analysis of pool and tailwater water quality,
- Comprehensive generic description of the "adverse impacts on water quality and stream uses...", and
- Presentation of mitigation measures applicable to TVA's impoundments.

Perhaps the most significant difference between the TVA study and the one conceived for this report is the size of the population to be analyzed. TVA operates a total of 47 reservoirs, of which 33 were discussed in their study. On a national scale, one is faced with thousands of reservoirs. TVA (1978) argues the following:

> "There are two possible methods for identifying and determining the extent of impacts from reservoir releases. The first method compares the releases from all structures to specific numerical criteria. This method simplifies problem identification and monitoring. However, the application of rigid, uniform numerical criteria may overlook the actual or highest value uses and needs upstream and downstream from a specific project. The second method determines the need for improvements on a case-by-case basis and emphasizes providing balanced protection of the water uses associated with each specific project without unduly penalizing any given project by the application of rigid numerical criteria. Although this method makes problem identification and subsequent monitoring efforts much more difficult, it provides the flexibility needed to optimize resource management."

For the scope of TVA's study, a case-by-case approach is sensible. However, for the purposes of this report to Congress, "problem identification" is required as a necessary first step towards a national strategy to "optimize resource management." Specific numerical criteria are used sparsely in this report to Congress. Also, recognizing the importance of in-depth investigations of specific sites, several case studies have been incorporated in this report to provide a high level of detail.

Several features of the TVA study have been adopted for this report. First, the water quality in both the impoundment itself and in the downstream tailwaters are examined. This report takes the analysis one step further and compares upstream water quality to downstream water quality to assess the changes in the vicinity of, if not caused by, the impoundment.

Second, the TVA study and this report present a generic description of the water quality effects associated with impoundments. In fact, much of the material included in this report's discussion of generic effects is taken from the TVA study. TVA also discussed generic effects on water uses. This was excluded from this report because, although important, this pertains more to resource management rather than problem identification. Furthermore, water uses are often designated based on water quality, making the assessment of uses somewhat subjective.

Finally, TVA presented a generic discussion of mitigation measures. This report also provides this information, much of which was taken from the TVA study.

A second approach to the subject is presented by the ORNL study (Cada, et al., 1983), which has the following abstract:

> "One of the environmental issues affecting small-scale hydropower development in the United States is water quality degradation. The extent of this potential problem, as exemplified by low dissolved oxygen concentrations in reservoir tailwaters, was analyzed by pairing operating hydroelectric sites with dissolved oxygen measurements from nearby downstream U.S. Geological Survey water quality stations. These data were used to calculate probabilities of noncompliance (PNCs), that is the probabilities that dissolved oxygen concentrations in the discharge waters of operating hydroelectric dams will drop below 5 mg/l. The continental states were grouped into eight regions based on geographic and climatic similarities. Most regions had higher mean PNCs in summer than in winter, and summer PNCs were greater for large-scale than for small-scale hydropower facilities. Cumulative probability distributions of PNC also indicated that low dissolved oxygen concentrations in the tailwaters of operating hydroelectric dams are phenomena largely confined to sites with large-scale facilities."

The ORNL study has the following major features:

- Evaluation of a population of power generating impoundments based on a survey of available data,

- Analysis of dissolved oxygen data from STORET (EPA's national water quality data base) using a numerical criterion and statistical methods,

- Analysis of tailwaters only, and

- Regional and seasonal evaluation of the data.

The ORNL study attempts to draw national conclusions based on the pairing of a power dam with available dissolved oxygen data meeting specified criteria. While national in scope, the study could not make the claim that the sites analyzed were representative. It is desirable for this report to Congress to be based on representative sites.

ORNL disaggregates available data geographically and seasonally. If sufficient data exist to provide a complete picture, data disaggregation can highlight the most pronounced results which may otherwise be buried in an aggregated data set. This report to Congress includes a revisitation of the ORNL study of dissolved oxygen to illustrate some of the advantages of disaggregation and its importance to the national perspective. Resource limitations precluded performing such an approach on all parameters including the pool and the tailwaters. However, this report does take the ORNL study one step further by identifying a representative sample of sites which moves toward an assessment of national scope.

A third approach to the subject is an ongoing study by the Army Corps of Engineers. Intermediate progress in this effort has been reported by Kennedy and Gaugush (1987). A brief summary of this study is obtained from the paper's abstract:

> "Increasing concern over the quality of freshwaters and growing emphasis on the development of improved methods for the management of its existing water resource projects, led to the initiation of several major water research programs by the U.S. Army Corps of Engineers. One such effort involves the compilation and analysis of a Corps-wide water quality database for reservoirs and tailwaters. These data are being supplemented with subjective information concerning enhancement needs solicited from field offices. The survey involves over 750 reservoirs, locks and dams, and dry dams. Most frequently cited during the survey were the need to improve tailwater conditions (particularly dissolved oxygen, temperature extremes, and the presence of reduced metals), reduce nutrient concentrations, and ameliorate conditions associated with the eutrophication process. A preliminary investigation of southeastern reservoirs indicated: 1) lower total nitrogen concentrations than the national average, 2) significant longitudinal gradients in water quality, and 3) turbidity and flushing rate as probable constraints to primary production."

The CE study has the following features:

- Evaluation of the CE water resources projects, which include reservoirs, locks and dams, and dry dams built predominantly for the purposes of flood control, recreation, and water supply,

- An analysis of dissolved oxygen as it compares to the physical features of a dam,

- Analysis of nutrients, metals, and dissolved oxygen in southeastern reservoirs by comparing discharges or releases and inflows based on STORET data,

- A growing season analysis as well as an investigation into water quality gradients in the pool, and

- Qualitative presentation of water quality issues in the pool and tailwaters.

Similar to the other two studies, Kennedy and Gaugush evaluate a much smaller population of impoundments than is of interest for this report to Congress. CE projects are also oriented towards flood control, recreation, and water supply as well as power production. The Corps of Engineers approach of comparing the physical features of a project to water quality status of tailwaters is promising because if such relationships can be found, nationwide assessments are greatly facilitated. Much more is known (or is easily obtainable) about physical features than is known about the water quality at unmonitored sites. Therefore, this report to Congress endeavors to identify those relationships where they may exist.

The Corps of Engineers, STORET comparison of paired inflow and discharge concentrations of a given parameter also is expected to be quite useful because it addresses the change in water quality that may be caused, or at least facilitated, by an impoundment. Identified changes may be both positive or negative. This report to Congress relies heavily on both STORET data and an analysis of water quality changes between the inflow and discharge. STORET is the EPA supported national computerized repository for water quality data (USEPA, 1982a).

The CE study approaches seasonality by performing a "growing season" analysis of nitrogen, phosphorus, and chlorophyll. The benefits of a seasonal approach have already been discussed, although the scope of this report to Congress has been limited to a seasonal analysis of dissolved oxygen.

Lastly, the CE report is addressing the water quality issues generically and reporting the frequency of occurrence of various types of problems. This approach was also used in the TVA study.

In sum, the three studies presented here by the TVA, ORNL, and CE offer a representative range of approaches and current thinking available for this national assessment. The analytical approach for this report to Congress was developed to take the most appropriate features of each--within budget and schedule constraints--in providing an informative overview to Congress.

## OVERVIEW OF REPORT CONTENTS

The major features of this report and their location in this document are as follows:

- A generic description of water quality concerns related to impoundments of all purposes including power production, navigation, flood control, recreation, water supply, etc. (Chapter II);
- A representative sampling methodology to arrive at a manageable sample from the 68,155 population of impoundments for analysis (Chapter III);
- A mixing analysis of impoundments to screen for stratification potential based on physical characteristics of a site (Chapter III);
- A seasonal and regional examination of dissolved oxygen in the tailwaters (Chapter III);
- An upstream/downstream comparison of concentrations of nutrients, metals, and dissolved oxygen to assess the changes facilitated by impoundments (Chapter III);
- An analysis of nutrient enrichment in the pool (Chapter III); and
- A presentation of case studies to examine site-specific situations (Chapter IV); and
- A generic discussion of mitigation measures applicable to water quality in the pool and/or the tailwaters (Chapter V).
- Agency assessments of approaches and need pertaining to water quality issues for their own programs (Chapter VI).

Each of these concepts has been used in prior endeavors except for the nationwide representative sampling. The purpose of sampling, if the available data support it, is to extrapolate results of the analysis to provide a national characterization of the issues to fulfill Congress' information needs in this area.

# II. WATER QUALITY EFFECTS OF IMPOUNDMENTS

This chapter presents an overview of the potential effects of impoundments upon water quality. Although attention is usually focused on unwanted effects, desirable changes may also result. An "ecosystem perspective" is necessary since issues are interdependent, in varying degrees, upon each other. If one condition within the reservoir - stream ecosystem is altered, its effects can ripple through the balanced system, positively or negatively affecting other facets of water quality. The following list is not exhaustive, but provides the major potential reservoir-stream ecosystem changes:

STRATIFICATION
- Low Hypolimnetic Dissolved Oxygen
- Increased Iron & Manganese
- Hydrogen Sulfide
- Denitrification
- Thermal Changes

EUTROPHICATION

OTHER CHANGES
- Gaseous Supersaturation
- Salinity Changes
- Sediment Movement
- Flow Regulation
- Reaeration Denial
- Fish Entrainment
- Toxics Accumulation

The above effects do not occur in every impoundment system. Their occurrence and magnitude depend on many factors, including depth of the reservoir, climate, watershed land use, reservoir siting, and reservoir features. Some--land use, siting, and reservoir features--are at least partially controllable, while others--climate--are uncontrollable. Certain geographic regions have their own dominant water quality concerns. A brief overview of each potential effect is discussed in the following sections.

## STRATIFICATION

Water quality effects in the discharges of reservoirs can result from seasonal warming and consequent thermal stratification of impounded waters (Cada et.al, 1983). However, not all reservoirs stratify and stratification, by itself, is not a water quality problem. The occurrence of this effect depends on several factors, including reservoir surface area, depth, volume, detention time, degree of protection from the wind, and climatic conditions of the geographical area (Cada et. al, 1983). For example, run-of-river impoundments are located on main stream rivers and are characterized by low head dams with impounded water not extending far from the natural channel. Detention times are on the order of a few days. Since water velocities are appreciable, significant vertical stratification typically does not occur (USEPA, 1973).

In contrast, storage reservoirs are generally located on tributary streams and are relatively deep, with the water surface extending far beyond the natural river channel. These reservoirs have a large storage capacity in relation to the drainage area and generally have a detention time of several months. They can be characterized by thermal stratification, usually of the classic three layer system, during the summer warm periods (USEPA, 1973). The upper layer is termed the epilimnion. A zone of rapid drop in temperature occurs below this and is called the thermocline. Below the thermocline is a zone of fairly uniform, cooler temperatures called the hypolimnion. In the fall, surface temperatures cool to the same temperature as the hypolimnion and the stratification is disrupted, with the impounded water completely mixing. The warmer climate of the Southeast and Great Basin regions results in thermal stratification occurring earlier in the year and remaining longer than in the Northeast or Northwest (Cada et al, 1983). A wind-driven turnover may also occur in the spring when there is no vertical temperature gradient.

Thermal stratification often results in stratification of important water quality chemical parameters, such as dissolved oxygen, metals, and nutrients. These parameters are discussed in more detail in the following sections. It is important to note that stratification is a natural condition that occurs in many lakes. The important difference between the lake and reservoir is that in a lake the epilimnetic waters, generally characterized by good water quality and reflecting the prevailing average ambient air temperatures, are released to an outflowing stream. In a reservoir, the hypolimnetic waters, which may have poorer water quality (in terms of dissolved oxygen, iron, and manganese) than the pre-impounded stream, can be released through low level outlets. Some dams are constructed so that water can be withdrawn at several different depths appropriate for discharge to the outflowing stream. As a result, the dam may not have a negative effect on downstream conditions. When reservoirs do not stratify and are mixed from top to bottom, the water discharged does not represent a particular zone and thus the depth of withdraw is not critical to water quality. Water quality effects associated with stratification may include low hypolimnetic dissolved oxygen, increased iron and manganese, hydrogen sulfide, denitrification, and thermal changes.

**Low Hypolimnetic Dissolved Oxygen (DO).**

During certain periods of the year, the denser waters of the hypolimnion remain relatively free from turbulence or other significant water motions, and have no opportunity for reaeration at the surface. Demands on oxygen are present because of bacterial decay of organic matter, resulting in oxygen-poor or anoxic waters. Anoxic bottom waters in reservoirs cannot support fish and other aquatic life. Furthermore, when large volumes of low DO water are released, downstream waters are also adversely affected. Eventually, through turbulent reaeration processes downstream, DO levels return to normal.

Low tailwater DO concentrations generally occur where reservoirs remain stratified for longer periods and contain relatively warm waters (Cada, et al., 1983). The distance the stream needs to recover may be great enough to lower the stream's assimilative capacity for oxygen demanding wastes from downstream sources. The anaerobic conditions of the hypolimnion are also harmful to water quality since it may cause several chemical reactions to occur, such as release of metals, phosphorus, iron and manganese from bottom sediments. Increases in iron, ammonia, manganese, silica, phosphate and sulfide ions, and soluble organic compounds have been observed in anoxic waters in contact with bottom sediments. In the fall and spring, uniform vertical temperatures result in periods of mixing called the fall and spring turnovers. During these times, soluble materials entrapped in the hypolimnion, such as inorganic nutrients, iron and manganese and organic material, are returned to the biologically active surface waters. The nutrients become available to support primary production and sometimes result in fall and spring plankton blooms observed in many reservoirs and lakes (USEPA, 1973).

**Increased Iron and Manganese.**

A water quality problem directly tied to the anoxic waters of a hypolimnion is the increased concentrations of certain metals, especially iron and manganese. Reservoirs not stratified and thus without an anoxic hypolimnion usually act as sinks for these metals, which remain adsorbed to bottom sediments. However, under anoxic conditions these insoluble metals may become soluble and are released from the sediments, into reservoir waters as well as downstream waters. Metals in significant concentrations can be harmful to fish and other aquatic life and contaminate water supplies. When waters are aerated in the spillway, iron and manganese become oxidized and precipitate out of the water, being deposited upon and causing discoloration of structures and the stream bed of the tailwaters. Soluble iron oxidizes rather rapidly, so that the effect on downstream waters is limited, but soluble manganese oxidizes much more slowly and therefore impacts a much larger area downstream (TVA, 1978). High concentrations of either soluble iron or manganese can adversely impact downstream water supplies by staining plumbing fixtures and laundry, affecting the taste and aesthetic quality of the water, and interfering with manufacturing processes.

**Hydrogen Sulfide Production**.

Under anaerobic conditions of the hypolimnion, sulfate, a common constituent of streams, is reduced to hydrogen sulfide ($H_2S$). If present in sufficient concentrations, $H_2S$ can reach levels toxic to fish in the reservoir and downstream waters. Hydrogen sulfide can also be an odor problem if enough is released into the atmosphere. Finally, where reservoirs are used for supplying water for domestic use, sulfur compounds can adversely affect water taste and lower water hardness.

**Denitrification**.

Denitrification only occurs in the absence of dissolved oxygen. Facultative, anaerobic bacteria use nitrate and reduce it to produce nitrite as an intermediate product, with the final principal end product being nitrogen gas--a nitrogen form not utilizable by most organisms. Denitrification therefore acts as a nitrogen sink. Denitrification can be an important process in stratified, eutrophic impoundments, where anoxic conditions occur in the hypolimnion in the summer months. The loss of gaseous nitrogen changes the nutrient balance.

**Thermal Changes**.

Because stratification generates layers of warmer and colder waters, the water withdrawn for release, depending upon the inlet depth, may be warmer or colder than pre-impoundment conditions. Some stratified systems are themselves beneficial by providing habitat for cold water fish and warm water fish. Their use for heat exchange in fossil or nuclear power generation or for pump storage operations can add thermal energy or turbulence; the stratification regime could be altered.

In cold water streams an increase in temperature may be sufficient to adversely impact the fish population inhabiting the system. This adverse impact has a high potential for the cool water systems in the South, since most of the streams are close to the temperature borderline for classification as cool water streams (SCS, 1979). The elevated temperatures may not be adverse to warm water fish (SCS, 1979). Fish can acclimate to rising temperatures if the rates of increase remain gradual, but death occurs once their absolute thermal ceiling is reached (Schwiebert, 1984). The receiving stream will eventually approach or reach the natural stream temperature, but the distance required depends on many factors, such as canopy cover and groundwater flow (SCS, 1979). Sometimes the release of cold-water discharges of large reservoirs, like the Ozark and Tennessee River tailwaters, can create new cold-water fisheries downstream (Schwiebert, 1984). The Peapacton Dam on the east branch of the Delaware River transforms a marginal trout river into one of the best major trout streams in the East (Schwiebert, 1984). Reservoir construction on the San Juan in New Mexico changes a coarse-fish habitat into an excellent rainbow fishery due to cold water discharges (Schwiebert, 1984). Impoundments and resulting tailwaters in the southern states creates a trout fishery resource equal to hundreds of miles of natural coldwater streams (Pfitzer, 1974). Some of these states do not have a significant natural trout fishery.

Fisheries created by impoundments may only be seasonal however, if the volume of cold water stored in the reservoir is insufficient to allow releases to occur until the fall turnover. At that time,warm water is released into the tailwaters. As a result the tailwater is too cold in spring and early summer for warm-water fish production and too warm in late summer and fall to support cold-water fisheries (Pfitzer, 1974).

## EUTROPHICATION

Eutrophication is a natural process that occurs not only in reservoirs, but also in natural lakes and other water bodies, particularly those which have low velocity rates. This process involves increased growth and death rates of aquatic plants, usually resulting from the addition of high levels of nitrogen and phosphorus. Since algae are at the base of a complex food chain, there are numerous effects on higher plants and animals when the population and diversity of algae are changed. Furthermore, eutrophication and stratification can have compounded effects. Dead algae settle into the hypolimnion and increase demands on scarce oxygen resources through bacterial decay. Algal blooms degrade reservoir quality by triggering imbalances in the oxygen cycle to which other organisms, such as fish and smaller food-chain organisms, are sensitive. Excessive growths of certain blue-green algae can also cause taste and odor problems in drinking water. During the day, the excessive growths of algae produce DO through photosynthesis, but at night, algal respiration depletes DO concentrations and produces carbon dioxide which reduces pH. These daily fluctuations in pH and DO can have detrimental effects on other biota. Once algae die, DO used in their decomposition can significantly lower DO levels, particularly in the hypolimnion.

The anaerobic environment of the hypolimnion can increase eutrophication by causing releases of phosphorus that would normally be adsorbed to bottom sediments. This release can initiate a transfer of soluble phosphorus from the sediment to hypolimnion to epilimnion and provide nutrients during the growing season. When the lake destratifies or completely mixes, the soluble phosphorus is also most available for algal utilization although this typically occurs at the end of the growing season.

Eutrophication can also include the excessive growth of rooted aquatic plants, that detract from aesthetic qualities, reduce recreational opportunities, and also deplete DO resources when they die. Eutrophication therefore may hinder recreational use of a reservoir and impair its value as a low cost treatable water supply. Advanced eutrophication is generally thought to be undesirable, but a moderate amount of nutrient enrichment can result in a desirably productive system, oftentimes with improved sport fishing opportunities.

## OTHER CHANGES

There are a number of other changes associated with impoundments that can affect water quality. These are not directly related to stratification or eutrophication and are, therefore, presented separately. They include gaseous supersaturation, salinity changes, sediment movement, flow regulation, reaeration denial, and fish entrainment.

### Gaseous Supersaturation.

In reservoirs, supersaturation of gases can occur as the result of several processes. The most common manner in which impoundments may cause supersaturation is the interaction of air-water mixtures under pressure in spillways and sluiceways which can entrain air into deep turbulent stilling basins where excessive gases are dissolved. The injection of air, or reaeration of the hypolimnion may also contribute to a state of supersaturation. A third cause is heating which lowers the saturation point. An example of this occurs in the spring when a reservoir receives gas saturated cold runoff water and is also recharged with gases during the turnover. As the water is heated through, seasonal warming supersaturation may occur (Bouck, 1980). Dissolved oxygen is extremely bioactive and is not a problem, but dissolved nitrogen is biologically inert in vertebrates and, therefore, can cause gas bubble disease, a disease analogous to the "bends" experienced by divers. The extent of this occurrence depends on vertical velocities in the tailwater, bubble size, the depth to which the bubbles are carried, turbulence, initial concentration of dissolved gases, and water temperature (TVA, 1978). As the water flows downstream the nitrogen concentration tends to equilibrate with those of the atmosphere. The length of the stream reach before equilibrium depends on the rate of flow and the physical characteristics of the stream channel (TVA, 1978).

### Salt Concentrations.

When water evaporates, any salts present are left behind, causing an increase in salt concentration. In arid regions and areas where salts are relatively abundant in the watershed runoff, salinity levels can reach critical proportions. Reservoirs, by virtue of their increased surface area, increase losses in regional water budgets through greater evaporation. Salinity may also increase in reservoirs receiving return flows from irrigation. Many freshwater fish and other aquatic life that are intolerant to relatively high or fluctuating salt concentrations cannot survive such conditions. Water with critical salt levels is also difficult and expensive to treat for human consumption.

Not all reservoirs have a negative effect on salt concentrations. For example, some flood control reservoirs in the arid west store high quality flood flows in the spring and release required flows in the fall and winter, greatly improving salinity downstream. In Lake Mead, dissolved materials normally kept in solution by carbon dioxide are precipitated in the reservoir, thus decreasing salinity downstream.

**Sediment Movement**.

Waters received by reservoirs generally carry higher sediment loads than waters released from reservoirs. Suspended sediment received by the stream from the upland erosion, along with channel erosion, is carried downstream. When the streams enter a quiet body of water, the sediment load drops out. Reservoirs, therefore, act as large settling basins. Reservoirs may fill up as a result of this process which must either be anticipated in design or mitigated by dredging.

Often, horizontally stratified currents within a reservoir, called density currents, carry greater sediment loads than the rest of the reservoir. These currents may then be tapped for release downstream by regulating multiple-outlets, a feature common in many newer dams. Regulation of these currents facilitates sediment releases and can reduce the frequency of dredging and sluicing operations. Episodic intentional releases of silt laden bottom waters to rid the impoundment of silt can cause short term high turbidities, sudden unwanted depositions, smothering of aquatic life, and unsuitable conditions for fish spawning. Alternatively, low suspended solids releases can cause increased scouring of stream channels as the stream seeks an equilibrium of sediment load.

Furthermore, sediment can be partially or completely composed of organic material. The organic material can decompose by biotic action and cause oxygen depletion in the water column over the sediment. This oxygen depletion is called sediment oxygen demand. It can be significant in the balance of oxygen within reservoirs. The organic material in the sediment can come from point or nonpoint sources, organic growths in the inflowing stream or from the organic processes within the reservoir itself.

Sediment changes do not always have to occur. If a reservoir is operated to convey sediment density currents through the reservoir, in time an equilibrium can be achieved where the inflow and outflow of suspended sediment are equal.

**Flow Regulation**.

Dams typically cause modified flow conditions when operated for water supply, recreation, hydroelectric power, or other uses. The use of reservoirs to regulate streamflow can have a positive effect on water quality. If the dam is operated such that low flows are augmented, a stream's assimilative capacity can be enhanced and the concentration of pollutants already present downstream can decrease (provided the reservoir water has lower pollutant levels). When dams are used for flood protection, extremely high flows are avoided, as are associated suspended sediment load problems and other serious water quality problems related to flood water.

If, however, the dam is operated such that it produces a lower than normal low flow, downstream assimilative capacity for downstream discharges may be reduced. A lower than normal low flow can also greatly affect aquatic habitats by increasing water temperatures, decreasing surface area, depth of riffles and pools, and stream width. There is much less habitat, reduced food-chain organisms, reduced fish nursery and spawning acreage, and fish are more exposed to predators and more susceptible to disease (Schwiebert, 1984). Tailwaters without minimum flow discharges greatly reduces aquatic insect production since major shoal and riffle habitat areas are exposed (Pfitzer, 1974). A higher than normal high flow can create a severe scour and bank erosion problem as well as the possibility of flooding. High flows can produce velocities that some aquatic biota cannot tolerate unless some "slack water" habitat is available. Flow regulation can sometimes improve the composition of the aquatic community. It has been suggested that the retarding of storm flows is a primary reason for the much larger benthic populations and improved species diversity found downstream of southern SCS flood retention impoundments (SCS, 1979). For intermittent streams, the longer duration of flow by the release of stored flood flow may cause a benthic population improvement (SCS, 1979).

Impoundments also can have a chemical stabilizing effect on the receiving streams because the impoundments reduce the inflowing peak concentrations. Chemical concentrations would fluctuate more erratically in the inflowing stream than in the receiving stream (SCS, 1979). One positive use of dams that has been proposed for the Yakima River in Washington is increasing the upstream storage of a reservoir for fish flow enhancement. It is predicted that some 340 miles of spawning, rearing and resting areas for steelhead and salmon in the Yakima River System can be improved by this proposal (Dompier and Woodworth, 1980).

Reaeration Denial.

Dams slow waters down, decrease turbulence and thus decrease natural transfer of oxygen from the air to the water by reaeration. At a non-power dam with a spillway, the rapid flow of the water over the spillway and subsequent tail water turbulence, promote reaeration of the tail waters. In power impoundments, water reaches the release point by transport in a closed conduit having given up some of its kinetic energy to the turbines. Reaeration under this condition partially depends on the nature of the point of release, with submerged releases providing less aeration than free-falling releases. The retrofitting of existing unused mill ponds and impoundments with add-on low head small hydropower turbines is a particular example of where this effect may be noticeable.

Fish Entrainment.

Fish entrainment is the capture and passage of fish through turbine machinery during power generation operations. In addition to the reduction of fishery resources of the reservoir system, the discharge of dead fish and their remains can cause water quality problems from an aesthetic viewpoint. If discharged in significant quantities, the dissolved oxygen demands of their decomposition may depress available oxygen. Because there has been much recent interest in this issue, fish entrainment is mentioned in this report even though it is not a water quality issue per se.

Toxics Accumulation.

Sediments trapped behind dams can be contaminated with toxic metals and/or organics. Normally, these toxic-bearing sediments are not transported downstream unless the sediments are disturbed as a result of dredging, dam removal, or dam failure. An example of this phenomenon occurred in the Hudson River where large amounts of polychlorinated biphenyls (PCBs) were transported downstream when the Fort Edward Dam was removed in 1973 (Carcich and Tofflemire, 1982). Analysis of toxics accumulation behind dams was not included in this report due to insufficient data on a national level.

# III. EPA ANALYSES

## OBJECTIVES

The previous chapter describes the generic effects that are possible. The objective of this chapter is to make quantitative estimates of the national scope of the effects that dams have upon water quality.

This chapter summarizes the methodology for estimating the scope of effects. Despite the fact that a statistically valid, quantitative approach is used, the estimates presented are highly qualified due to limitations in data availability. These estimates are based upon publications, written by experts in this topic, and upon monitoring data, contained within the EPA STORET water quality data repository. Two parallel paths are followed. What current publications are enlightening about the scope of water quality effects of dams? What can be inferred by examination of a random sample of the population of all 68,155 dams?

The objective is to make the estimation as simple, straightforward, and accurate as possible. The goal is to communicate the essential and basic aspects of dam water quality effects to nonspecialists. Qualifications are made throughout about the preliminary nature of the quantification.

Given the overall goal of quantification, a number of conditions are imposed upon its achievement:

- No new field data are involved in the analyses, although new data would further reduce uncertainty.
- The findings are to be unbiased and scientifically sound.
- Results are to be reproducible.
- Assumptions and limitations are to be stated.

The organization of this chapter is directed at answering the following questions.

- How many dams of various types are there?
- Where are the dams?

- What elementary theories and models can be utilized, given the information at hand, to assist the reader to understand some basic aspects of dam behavior? Note that the appeal of simple models is to provide generalities for problem identification and enlightenment and not to solve site-specific problems. Models appropriate for site-specific problems tend to be much more complicated and out of reach of the available resources of this report.

- How many impoundments have the potential to stratify, possibly facilitating water quality problems?

- What is the extent of the tailwater dissolved oxygen effect?

- How many dams alter water quality as streamflow passes through the impoundment?

- What is the extent of phosphorus enrichment, which is one requirement for imminent, ongoing, or advanced eutrophication?

The first three questions are addressed in the following section on "Preliminaries" or in Appendix C "Analysis Supplement." The last four questions are addressed in four subsequent sections of this chapter titled "Mixing Analysis," "Dissolved Oxygen in Dam Tailwaters," "Upstream/Downstream Comparison of Water Quality," and "Phosphorus Enrichment Analysis" respectively. For each of these latter questions, an attempt is made to identify any correlation between dam type and water quality. The mixing analysis and tailwater DO analysis are related since a poorly mixed (stratified) reservoir is much more likely to have tailwater DO problems.

**PRELIMINARIES**

This section presents a logical and strategic context to aid the reader in following the various analyses. The population of dams and their associated data are discussed. Ancillary data, not in the Corps of Engineers' data base, but added to random samples to fill in missing data, are also discussed. The general approach to sampling is presented and the topic of appropriate sample size is addressed. Elementary modeling tools, which are used in the chapter, are discussed and qualified in Appendix C, as is the significance of correlations associated with various sized samples.

## The Population and Associated Data.

The Corps of Engineers' data base includes 68,155 dams built up to the year 1980. This data base includes the following basic data:

- Coordinates: latitude and longitude; this allows a particular dam to be isolated and ancillary data, such as for water quality, obtained.
- **V** = volume of normal pool (acre•feet).
- **H** = hydraulic height of dam (feet).
- **Q** = flow capacity of the spillway to pass floodwaters (cfs).
- Installed hydropower of 100 kilowatts (kW) or more (100s of kW if known).
- Other identifiers: Corps of Engineers assigned number, state, name, uses such as power, flood control, etc.

The limitations of the Corps of Engineers data base are the following:

- There is no information on water quality
- Dams built since about 1980 are not included.
- Dams with less than 100 kW of power generation capacity are not labeled; there are numerous small hydroelectric projects in the United States.
- Small impoundments with volumes less than 50 acre•feet and having dams less than 25 feet high are excluded.
- The data base has no information on outlet level. Such information would be difficult to develop for the large numbers of dams in the United States.

To get numerical perspective on this population of dams, there are:

- 68,155 dams overall.
- 1,091 dams that are known to have more than 100 kilowatts of installed power.
- 301 dams that have more than 30 megawatts (MW) of installed power.
- 2,125 "large" dams with over 10,000 acre•feet of storage at the normal pool elevation. Of these, 424 have 100 kW or more of installed power, and 1,701 have no installed power.
- 66,030 "small" dams with less than 10,000 acre•feet of storage.

The dam inventory is partitioned, as to potential for incidence of water quality effects, using the knowledge contained in the generic effect descriptions and recommendations to the authors of this report from TVA experts:

- Large dams have potential for significant effects because they tend to stratify and have sufficient detention to trap nutrients.

- Dams with low-level outlets transmit water quality effects downstream associated with the hypolimnetic impoundment layer. It should be noted that power dams are most likely to have low-level outlets. Large nonpower dams may also have low-level outlets. Small dams are much less likely to have such outlets.

With this logic to support the partitioning, the Corps of Engineers' Dam listing is divided into three parts based on the criteria summarized in Table III-1. The partitioning is intended to focus resources on those subsets of the dam inventory wherein significant water quality effects are most likely. The geographic distributions of the three types of dams are depicted in Figures III-1, 2, and 3.

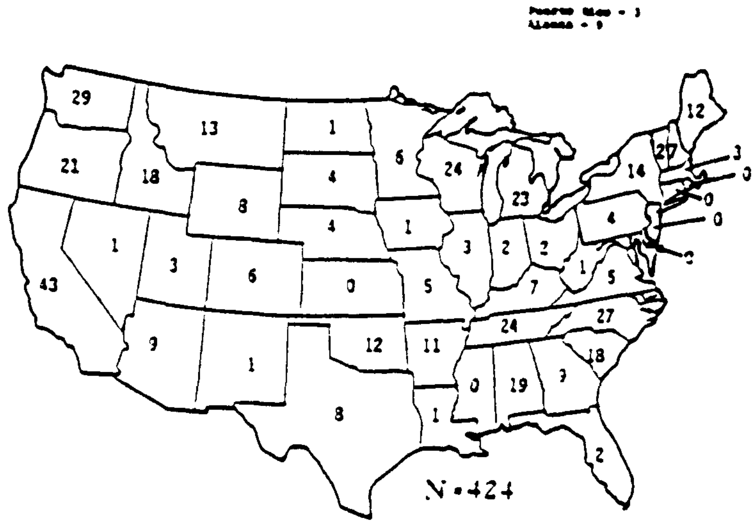
Table III-1. Partitioning Criteria.

| Type | Criteria | Number |
|---|---|---|
| Large Power Dams | Over 10,000 acre•feet and over 100 kW of installed power. | 424 |
| Large Nonpower Dams | Over 10,000 acre•feet and having no installed power. | 1,701 |
| Small Dams | All dams under 10,000 acre•feet (including 667 that have power). | 66,030 |

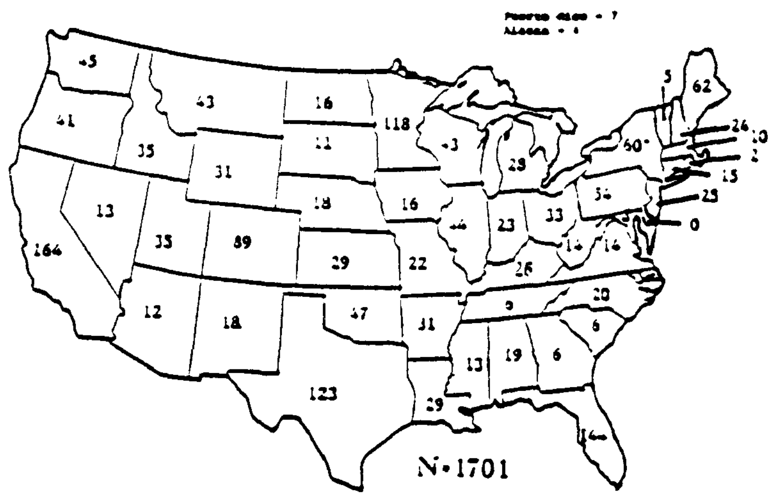
**Sampling**.

The general approach is to conduct a random sample of each of the partitioned data sets of dams in the Corps of Engineers data base. The sample is then utilized to determine some or all of the properties of the partitioned populations. For practical reasons of time and manpower constraints, it was decided that a sample size of 40 dams in each of the three partitioned data sets would suffice. The principal reason for a combined sample of 3 x 40 = 120 dams, is a large effort requirement to secure ancillary data for each dam.

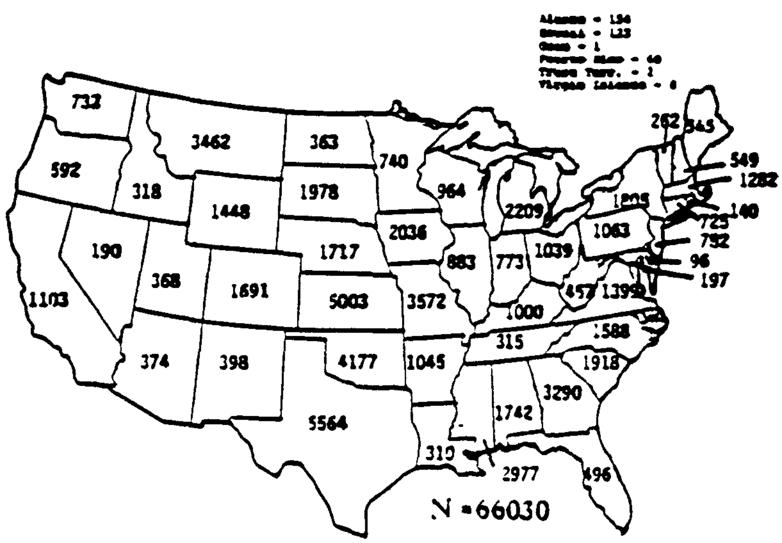
Once a random dam is identified, ancillary data are sought. These ancillary data elements include: impoundment surface area, length of impoundment along the flow axis, and average annual inflow. These geometric data are secured from USGS topographic maps and EPA's River




Population of Large Power Dams
Figure III-1




Population of Large Non-Power Dams
Figure III-2




Population of Small Dams
Figure III-3

Reach File. Also sought as ancillary data are water quality data above, within, and below the impoundment associated with the dam. These water quality data are obtained from EPA's STORET data repository using methods described in detail later in this chapter.

The partitioned random sample of dams is presented in Appendix B. Within this appendix are dam data taken from the Corps of Engineers' data base and ancillary data. Some, or all, of the following data elements are presented: identification number, name, installed power capacity, volume, hydraulic height, spillway capacity, latitude, longitude, mean inflow, area, length, Froude number, retention coefficient, mean phosphorus concentrations, and identification of dams having ancillary water quality data. (The Froude number and retention coefficient are explained later in this report.)

**Obtaining Sample Dams**

The sample of dams to be considered is randomly drawn from records contained in the 68,155-dam data base of the Corps of Engineers National Inventory of Dams. The various mathematical and statistical procedures are performed using the Statistical Analysis System (SAS), a commercial statistical software package (SAS Institute, 1982).

The dam population records are placed in a data base where analytical and statistical operations are performed. In all, 68,155 records were placed into the data base. The data base is sorted into the three dam categories: large power, large nonpower, and small dams. Each of these three categories represents a specific population. A random sample from each of these populations is developed using a SAS uniform distribution random number generating function. The SAS random numbers are used to select 40 random dams from each sub-population for a total of 120 random dams. A list of the random sample dams appears in Appendix B. The sample is partitioned to allow sufficient representation of the large power, large nonpower, and small dams. However, since the populations are of different sizes, the confidence bounds surrounding each sample vary.

**Other Logical Checks and Data Sources**

The sample size of 40, relative to its adequacy to represent the partitional data sets of dams, is discussed in Appendix C. It is shown that the theoretic confidence intervals are rather large, indicating that larger samplings are desirable to further define water quality attributes of dams.

After selection of each 40 dam random sample set, various checks are performed to confirm the representative nature of the sample. The geographic distribution is checked and the sample frequency functions are compared to the population frequency functions. The hypothesis is tested so that the sample and population are from the same distribution with 95 percent certainty. These checks are presented in Appendix C.

The Corps of Engineers dam data contained in the data base and associated with the random sample dams are supplemented with ancillary data. These data are:

- Estimates of pool area, impoundment length, and average inflow using equations found in Appendix C.
- Water quality data at upstream, pool, and downstream sites (as described in a subsequent section).

In addition to the random dams, information on other dams studied by the Oak Ridge National Laboratory, TVA, and the CE are incorporated into this chapter.

## MIXING ANALYSIS

The mixing analysis is the first of four major analytical efforts undertaken for this report. An approach is developed to categorize the stratification potential (indicative of little mixing) in the population of impoundments. This analysis is based on the Froude number which is suggestive of stratification. The potential for stratification should be investigated as an indication of poor mixing which, when accompanied by large oxygen demands, may result in low dissolved oxygen content and accompanying water quality problems in bottom waters. The potential for dissolved oxygen problems is estimated in two analyses (the Froude number analysis and the Oak Ridge National Laboratory analysis).

### Relationship of Froude Number to Mixing.

According to TVA, the potential for cold, deoxygenated hydropower releases from the hypolimnion of a reservoir is due largely to the effects of thermal stratification (TVA, 1987a). The degree of thermal stratification depends on hydrologic and morphologic characteristics that vary significantly across TVA reservoirs. Many strategies for release improvement either influence or are influenced by thermal stratification. When such strategies are under consideration for a wide range of reservoirs, it is useful to have a system whereby reservoirs can be ranked according to their stratification potential.

Thermal stratification insulates the reservoir hypolimnion from warming, inhibits mixing with the epilimnion, and sharply reduces natural reaeration of the hypolimnion. Without replenishment from the surface or tributary inflow, hypolimnetic oxygen can be depleted by organic decomposition and by respiration of aquatic plants. The effects of other important variables such as reservoir operations and inflowing organic and nutrient loads are highly coupled with thermal stratification in producing the ultimate water quality of the releases. In fact, these other variables can interact to produce significant vertical oxyclines (oxygen gradients) in the hypolimnion even in the absence of significant thermal stratification. In the southeastern United States strong thermal stratification generally produces a strong oxycline. Therefore, when used in combination with measures of other important variables, some index of stratification potential can be useful for ranking the potential for low DO, as well as cold temperatures in low-level releases. In this sense, the subsequent DO tailwater analysis and this analysis each support the other.

The densimetric Froude number represents the ratio of inertial forces imposed by the longitudinal flow to gravitational forces within the stratified impoundment; it is therefore a measure of the degree to which flow can alter the internal density structure of the reservoir. Small Froude numbers (less than about 0.3) indicate strong stratification potential, while larger Froude numbers indicate weak or intermittent stratification, progressing to completely mixed conditions for very large Froude numbers (TVA, 1987a). Furthermore, the Froude number can distinguish the greater stratification potential of a short, deep reservoir as compared to a long, shallow reservoir, even though the two reservoirs may have the same flow to volume ratio. For example, comparing reservoir flow to volume ratios and Froude numbers for Cherokee and Fontana Reservoirs, within TVA, indicates similar mean annual flushing rates, yet considerable difference in Froude number resulting from morphological differences.

The data in Figure III-4 represent a summer drought condition wherein inflows are low and hydraulic mixing potential is also low; however, the reservoirs with lower Froude numbers are also reservoirs with high top to bottom temperature differences. Figure III-4 shows average vertical temperature differential (surface to bottom) in TVA reservoirs at the peak of the 1986 drought versus the densimetric Froude number.

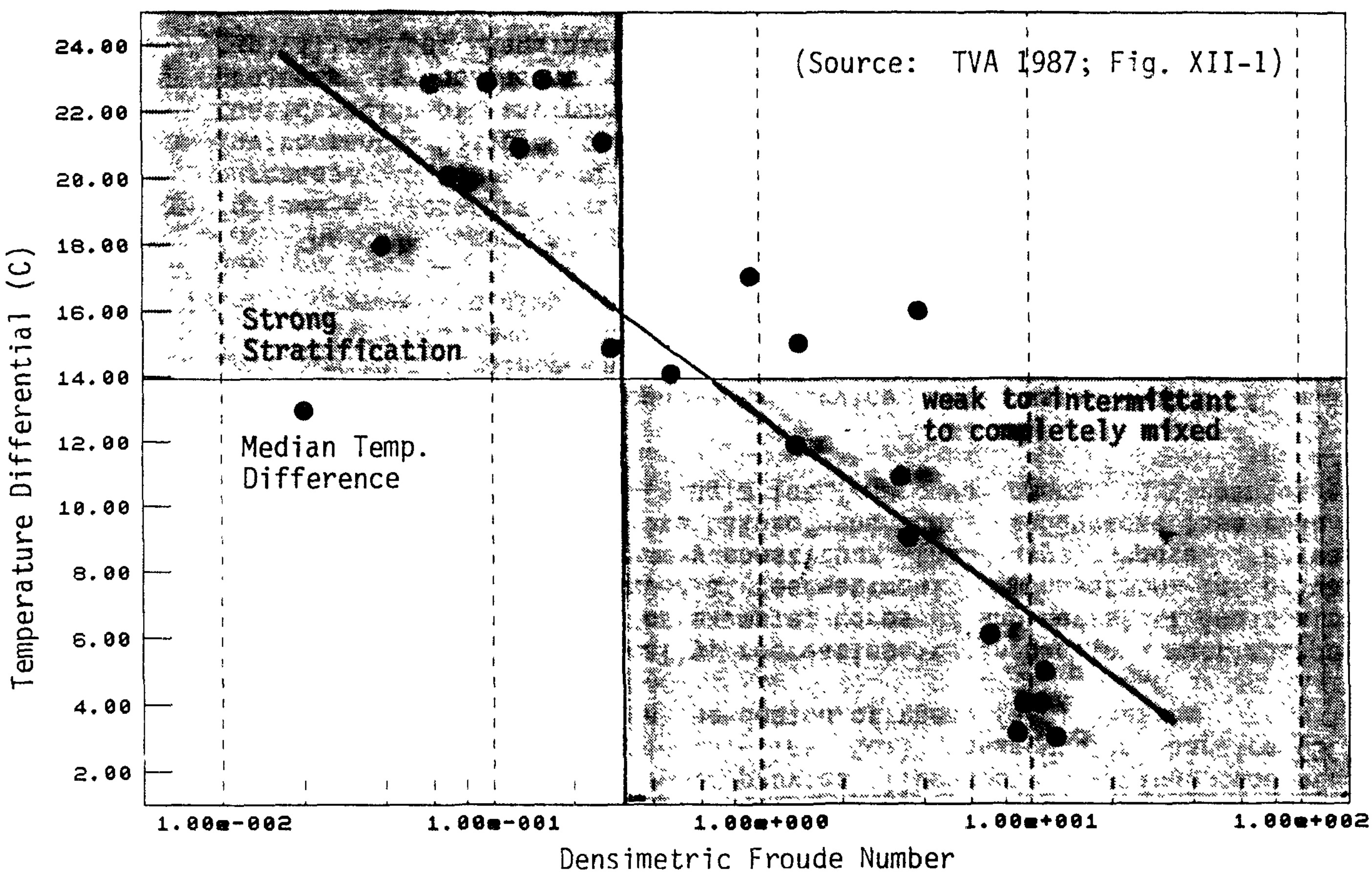



Figure III-4
Stratification versus Densimetric Froude Number for TVA Reservoirs.

For these reservoirs under these conditions, the densimetric Froude number is a significant index of stratification potential. The square of the correlation coefficient, $R^2$, which equals the percentage of explained variation, is 69 percent for this sample size of 22 TVA reservoirs under summer drought conditions. In other words, the variation in temperature differential between the top and bottom layers of TVA reservoirs is 69 percent explained by a linear relationship. TVA has suggested use of a seasonal Froude number (e.g., using only summer flows, volumes, depths, etc.) to improve the correlation, in lieu of annual average Froude numbers that were used to develop Figure III-4. Also shown in Figure III-4 is the **F** = 0.3 demarcation line between strong stratification and weak to intermittent stratification to mixed conditions. The vertical line defined by **F** = 0.3 and the horizontal line defined by the median temperature difference divide the 22 dams into two shaded subsets shown on Figure III-4. Eighteen of the twenty-two dams fall in the subsets. **F** = 0.3 provides a reasonable demarcation. Also there is a cluster of dams (6) around **F** = 10 that show the least temperature differential substantiating that there is less tendency to stratify (more tendency to mix) at high **F** values.

## Findings.

The national Froude number cumulative frequencies are utilized to make national estimates of mixing potential based on **F** = 0.3. The Froude number does not describe a condition of water quality - it does indicate the tendency of a reservoir to thermally stratify. A thermally stratified reservoir is a poorly mixed reservoir. A poorly mixed reservoir may have poor quality in the hypolimnion. If a reservoir has low-level outlets and poor quality water in the hypolimnion, the tailwaters may have poor quality. Poor, in this context, generally refers to low dissolved oxygen and the presence of iron and manganese.

The Froude number frequencies are estimated using the elementary model, $F = K\ (L/D)(q/V)$, where **K** depends upon units and **F** is dimensionless. A threshold for theoretic flow separation is $F = 1/\pi \approx 0.3$. This theoretic value agrees with the suggested TVA threshold. Above this level, there is a tendency to mix. At much less than 0.3, the tendency to stratify is strong.

The mixing tendency classification scheme enables determination of dam population percentages shown in Table III-2. Data for small dams are presented in Appendix E. Impoundments that are strongly mixed are unlikely to have as severe tailwater quality effects as stratified impoundments, provided other important factors such as inflow loadings and sediment oxygen demands are roughly equal. Strongly stratified impoundments may have water quality effects which may be transmitted downstream by low-level outlets. Without field inspections or some type of intensive polling, the incidence of such outlets is problematic. However, low-level outlets are more typical with power dams, but may occur in any dam.

Table III-2.
National Potential Mixing Percentages for Large Dams.

| Mixing Tendency* | Power | Nonpower |
|---|---|---|
| Potentially Strongly Stratified $F \le 0.3$ | 171 (40%) | 631 (37%) |
| Potentially Weakly or Intermittently Stratified or Completely Mixed. $F > 0.3$ | 217 (51%) | 742 (44%) |
| Missing Data | 36 (9%) | 328 (19%) |
| TOTALS | 424 | 1,701 |

*The **F** estimates utilized a large amount of large and some small dam data to generate values for **L**, **D**, **q**; however the linear estimators are forced through zero to enable small dam extrapolations of **F**. Therefore, the small dam tallies of potential strong stratification may not be as valid as the large dam tallies; these small dam tallies appear in Appendix E.

## DISSOLVED OXYGEN IN DAM TAILWATERS

The second of four major analytical efforts undertaken is an evaluation of dissolved oxygen concentrations in the tailwaters below impoundments. In particular, this effort reviews a study by ORNL and provides analogous results for the random sample and case study data collected for this report. Unlike the mixing analysis, this effort identifies dissolved oxygen problems as defined by the exceedance of a specific numerical criterion.

### Oak Ridge National Laboratory Study.

The U.S. Department of Energy has supported a Small-Scale Hydropower Development Program. Under this program, the Oak Ridge Laboratory conducted a water quality study of hydropower dam tailwaters (Cada, et al. 1983). The objective of the study is to estimate the extent of the problem of DO in tailwaters for small-scale hydropower development. This is analyzed by pairing operating hydroelectric sites with dissolved oxygen measurements from nearby downstream U.S. Geological Survey water quality stations. These data are used to calculate probabilities of noncompliance (PNCs), that is, the probabilities that dissolved oxygen concentrations in the discharge waters of operating hydroelectric dams will drop below 5 mg/l. Incorporated within this study are several technical judgments:

- A probability of noncompliance (PNC) is chosen as the statistic of interest because it directly addresses the question "What are the chances that discharges below a hydroelectric dam will violate dissolved oxygen criteria?" PNC is defined as the probability that concentrations of dissolved oxygen will be less than some specified value.

- Because thermal stratification and resultant oxygen depletion are seasonal phenomena, two probabilities are calculated for each site: one for the summer months (July, August, September, and October); and another for the remaining months, defined as winter months.

- The EPA criterion of a minimum dissolved oxygen concentration of 5.0 mg/l is utilized to assess the potential for water quality problems at small-scale hydroelectric projects (defined by the U.S. Department of Energy (DOE) as having a potential capacity of 30 MW or less).

- The data base for the U.S. Corps of Engineers National Hydropower Study is used, containing 15,300 existing dams.

- Dissolved oxygen data are acquired from the National Water Data Storage and Retrieval System (WATSTORE), maintained by U.S. Geological Survey. By cooperative arrangements, these data are a large subset of EPA's STORET data base.

- Selection of operating hydroelectric dams used in this study is based on the existence of appropriate water quality data in the USGS data base. A water quality monitoring station was considered appropriate if it (1) was downstream from the dam, (2) was within 4.8 km (3 miles) of the dam, and (3) had more than two measurements of dissolved oxygen concentration. No random sampling is included in the Oak Ridge study.

Of the 15,300 potential dams, 65 small-scale hydroelectric sites were selected for determination of PNCs. The study showed effects associated with season, geography, and whether or not the facility had greater or less than 30 MW of capacity. The PNCs tend to be higher in the summer, east of the Mississippi, and for facilities with greater than 30 MW.

**Findings.**

The method of analysis used in the Oak Ridge Study is applied in this study. The purpose is to determine if the methods and procedures of this study can reproduce the Oak Ridge results and, if so, to strengthen their previous findings. A summary in Table III-3 presents the comparison of the PNCs for the Oak Ridge Study and for this study.

The Oak Ridge PNCs are based on 139 power dams. Figure III-5 presents a geographical breakdown of the regions for the Oak Ridge study. Table III-3 summarizes the ORNL data as well as data available for 23 power dams from the large power sample of dams and the case studies. (Some sites in both the ORNL and EPA analyses lacked either summer or winter data.) The individual PNCs are presented in Appendix B for these power dams as well as for the nonpower dams. The STORET water quality data, which includes WATSTORE records, produce results comparable to the Oak Ridge Study. A significant finding is the confirmation of the seasonality of PNC levels and their relative magnitudes reported in the Oak Ridge Study. From the perspective of where and when dissolved oxygen levels are below EPA criteria, the combined PNC results indicate:

- PNCs vary regionally, seasonally, and with size for generating facilities.

- In the Ohio Valley and the Southeast there is a significant probability of low DO - 0.31 to 0.56. The probability is highest in summer months.

The next section makes dissolved oxygen comparisons of annual means to establish differences above and below dams. The use of the annual mean tends to reduce the ability to detect significant differences. Thus, the findings associated with mean annual effects should tend to be conservative. For example, if 10 percent of a sample shows significant difference on a mean annual comparison, the PNC seasonal results lead one to the conclusion that the seasonal effect will be larger than 10 percent.

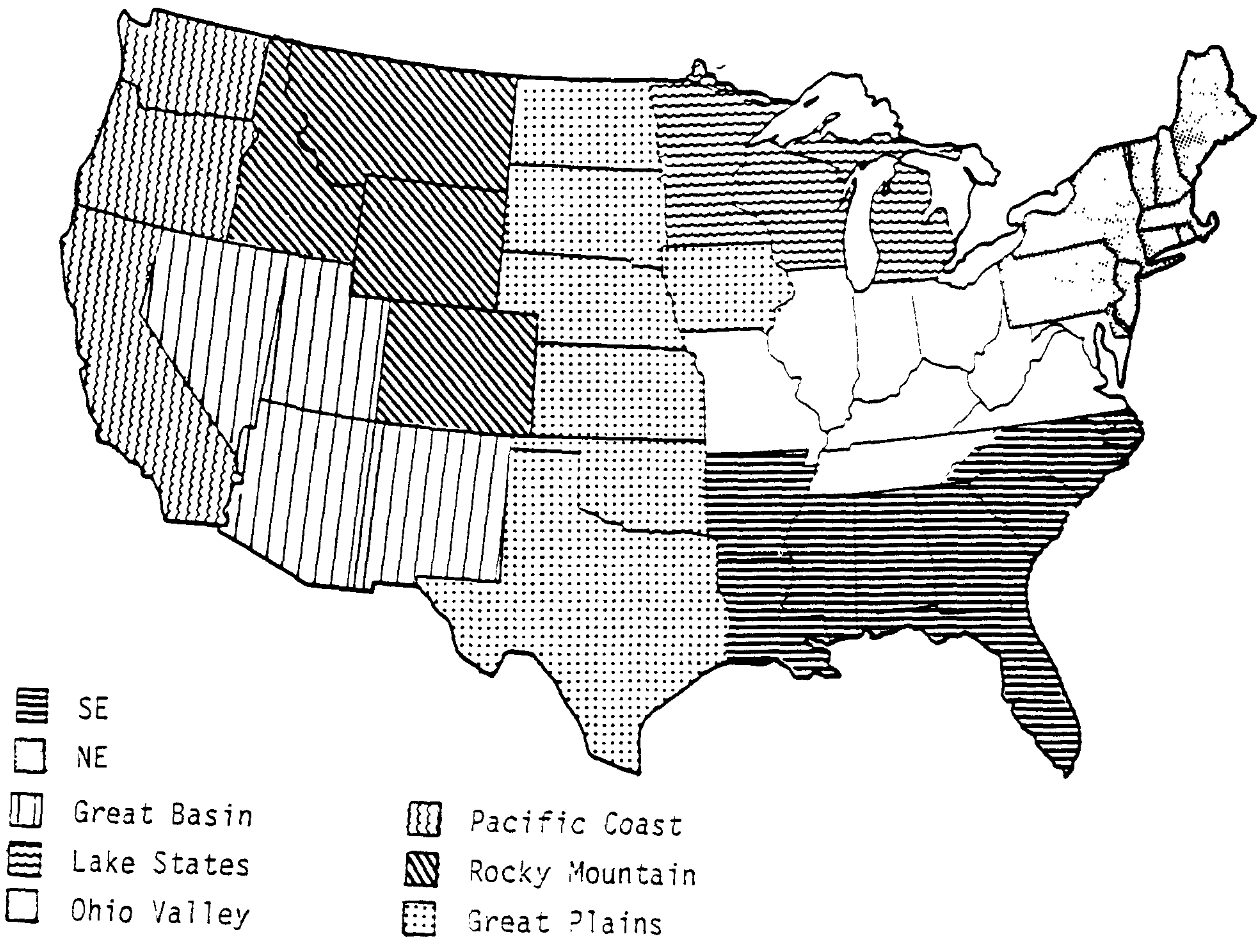



Figure III-5.

Geographical Breakdown of Regions for the Oak Ridge National Laboratory Study.

Table III-3.
Probabilities of Non-Compliance with
5 mg/l Dissolved Oxygen for Power Dams.

| | Oak Ridge National Lab | | This Study | |
|---|---|---|---|---|
| **Summer Season** | Capacity > 30 MW | | | |
| Location | n | PNC | n | PNC |
| Great Basin | 3 | 0.004 | - | - |
| Great Plains | 6 | 0.182 | - | - |
| Lake States | - | - | - | - |
| Northeast | 3 | 0.144 | - | - |
| Ohio Valley | 16 | 0.404 | 5 | 0.560 |
| Pacific Coast | 19 | 0.039 | 4 | 0.053 |
| Rocky Mountain | 6 | 0.052 | 2 | 0.000 |
| Southeast | 18 | 0.308 | 2 | 0.170 |
| (n) Mean | (71) | 0.162 | (13) | 0.196 |
| **Summer Season** | Capacity ≤ 30 MW | | | |
| Great Basin | 3 | 0.373 | - | - |
| Great Plains | 1 | 0.000 | 1 | 0.000 |
| Hawaii | 1 | 0.000 | - | - |
| Lake States | 5 | 0.043 | 4 | 0.123 |
| Northeast | 15 | 0.066 | - | - |
| Ohio Valley | 3 | 0.111 | 3 | 0.220 |
| Pacific Coast | 7 | 0.003 | - | - |
| Rocky Mountain | 9 | 0.027 | - | - |
| Southeast | 17 | 0.131 | 2 | 0.190 |
| (n) Mean | (61) | 0.084 | (10) | 0.137 |
| **Winter Season** | Capacity > 30 W | | | |
| Great Basin | 3 | 0.000 | - | - |
| Great Plains | 6 | 0.008 | - | - |
| Lake States | - | - | - | - |
| Northeast | 3 | 0.005 | - | - |
| Ohio Valley | 18 | 0.096 | 5 | 0.102 |
| Pacific Coast | 19 | 0.000 | 4 | 0.015 |
| Rocky Mountain | 6 | 0.000 | 2 | 0.000 |
| Southeast | 18 | 0.039 | 1 | 0.080 |
| (n) Mean | (73) | 0.021 | (12) | 0.049 |
| **Winter Season** | Capacity ≤ 30 MW | | | |
| Great Basin | 3 | 0.027 | - | - |
| Great Plains | 2 | 0.508* | 1 | 0.000 |
| Hawaii | 1 | 0.000 | - | - |
| Lake States | 6 | 0.005 | 3 | 0.003 |
| Northeast | 16 | 0.010 | - | - |
| Ohio Valley | 3 | 0.001 | 3 | 0.073 |
| Pacific Coast | 6 | 0.000 | - | - |
| Rocky Mountain | 9 | 0.000 | - | - |
| Southeast | 18 | 0.010 | 2 | 0.005 |
| (n) Mean | (64) | 0.007 | (9) | 0.020 |

* Presumed outlier.

The Corps of Engineers has also performed an analysis of tailwaters for low dissolved oxygen (Kennedy and Gaugush, 1987). Their study examined 73 Corps of Engineers hydropower projects concentrated in the pacific northwest and southeastern regions of the U.S. As shown in Figure III-6, low DO tailwaters are more frequently a problem in the southeast. This figure is the result of a Corps of Engineers questionnaire. A similar approach is presented in Chapter VI; the Chapter VI presentation extends and broadens the Corps of Engineer questionnaire approach to include TVA and Bureau of Reclamation projects.

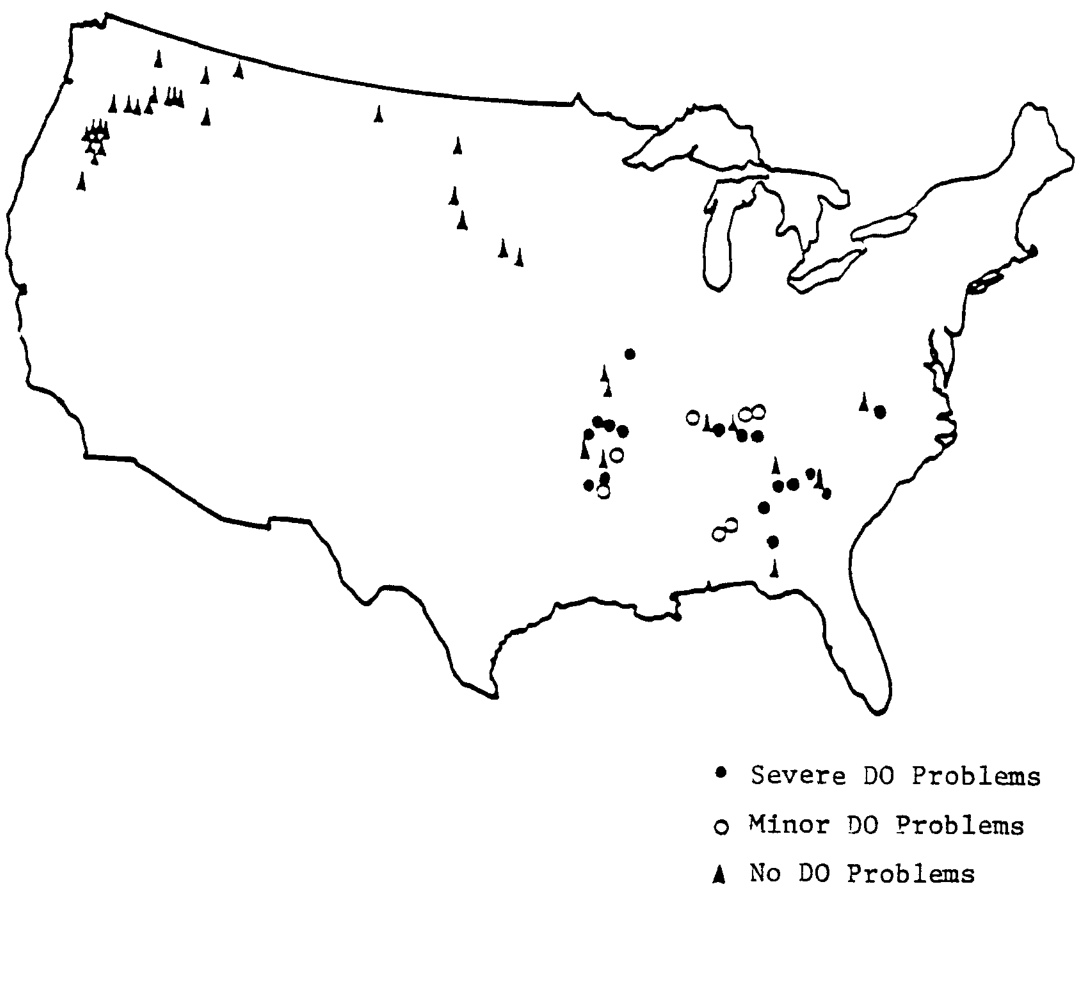



Figure III-6. Distribution of 73 Hydropower Projects and Their Tailwater Conditions. (Source: Kennedy and Gaugush, 1987)

## UPSTREAM/DOWNSTREAM COMPARISON OF WATER QUALITY

This section presents the third of four major analytical efforts comprising this chapter. Water quality data retrieved from EPA's STORET data base upstream and downstream of impoundments were collected and are compared. Changes in water quality observed as the result of passing through the impoundment are reported. The analysis is attempted on the random sample for a number of water quality parameters.

### Acquiring Water Quality Data.

The water quality data acquisition phase of this analysis is the collection of ancillary water quality monitoring data for the sites randomly selected from the population. The definition of the dam site requires the manual study of USGS and hydrological unit maps to determine the scope of the reaches to be studied. Reaches within the pool, upstream of the pool, and downstream of the pool are determined. The data search could reach out up to 20 miles from the dam, but such a distant search was infrequent. Latitude and longitude are used to define a "window" to be searched for water quality information.

If major changes in the hydrography occurred within these limits (such as another dam five miles upstream) the "windows" are made smaller to exclude extraneous, downstream backwater, or misleading data. The types of water quality and related parameters retrieved for this study are: mean streamflow, dissolved oxygen, phosphorus, nitrogen,turbidity, water temperature, iron, manganese, hydrogen sulfide, chlorophyll-a, and $BOD_5$.

Retrieval of data from STORET requires the use of the latitude, longitude polygon and the water quality parameters. The STORET system retrieves water quality data inside the polygon "window". The water quality data include station information (agency, location, name, depth of sample) as well as data on the water quality parameters. The upstream, downstream, and pool retrievals are placed into intermediate data sets; which are combined into a unique dam site file. SAS can be used to calculate the number of records, the maximum, minimum, mean and standard deviation values for each parameter in this combined site file. Information in Appendix B presents the incidence of ancillary water quality data for each dam in the random sample.

The arithmetic mean, standard deviation, maximum, and minimum values are calculated for each parameter at each dam. The resulting statistics are then downloaded into an RBASE data base; RBASE is a commercial software package that operates on personal computers. Of the original sample containing 120 impoundments (40 large power [L-P]; 40 large nonpower [L-NP]; and 40 small [S] dams), 65 impoundments (or 54%) had data for one or more parameters (39 L-P, 21 L-NP, 5 S). The L-P dams averaged 25 stations, L-NP averaged 8 stations (with the exception of Lake Tahoe with 301 stations), and small dams averaged 8 stations reporting data. STORET retrieval summarizations are presented in Appendix C.

Limitations of the Water Quality Data.

For many random sample dams, water quality data are not obtainable with the methods described herein. For such dams, then, an effect is either present or it is not, and this simple either/or provides a boundary on the estimate. In some cases, a very large number of the dams in the random sample have no water quality data.

Consider the following example of a hypothetical effect above and below a sample of 40 dams:

- 10 dams have significant effect
- 18 dams have insignificant effect
- 12 dams have no data

To estimate the upper bound of the number of dams having a significant effect, assume all dams without data (12) have a significant effect, therefore:

$$\text{Upper bound} = \frac{10 + 12}{40} = 55 \text{ percent}$$

Conversely, a lower bound can be approximated by assuming all dams without data (12) have an insignificant effect as follows:

$$\text{Lower bound} = \frac{10}{40} = 25 \text{ percent}$$

Thus, one can assume for this hypothetical example that between 25 percent and 55 percent of the dams exhibit a significant effect.

The difference in means testing is based on all data available at a site. The tailwater analysis of dissolved oxygen highlighted the fact that summer dissolved oxygen depressions are more prevalent than winter depressions. Therefore, there may be sites that show no significance in dissolved oxygen differences by annual means testing that would be significant if summer data alone were examined. This may be true for other parameters, particularly iron and manganese.

A data limitation may be the fact that many agencies enter data into STORET. Such data may have different levels of accuracy and quality control. The probability of noncompliance study conducted herein gives similar results to the Oak Ridge National Laboratory. Furthermore, an audit of the agency codes that identify the STORET contributors gave the following agencies: USGS, TVA, several Corps of Engineers districts, EPA, and water quality state agencies in Florida, Michigan, Wisconsin, California, Pennsylvania, and Iowa. These agencies' data are the data used to support the tailwater dissolved oxygen work discussed herein and provide insight into typical sources of STORET monitoring data.

## Statistical Comparison of Means.

This section discusses the statistical comparison of the means of water quality samples collected above and below the dam. Samples from the pool are excluded except for the phosphorus analysis presented later. The analysis applies statistical significance testing to the **difference of means** assuming the difference is normal.

There are three possible situations:

- The difference is positive and statistically significant; in this case, the average concentration is higher below the impoundment than above the impoundment.
- The difference is positive or negative and statistically insignificant; for this case, there is no significant difference above and below the impoundment.
- The difference of means is negative and statistically significant; in this case, the average concentration is lower below the impoundment than above the impoundment.

If there is no change in water quality above and below the dams, the expected distribution of differences[1] would be 5% decrease, 90% the same, and 5% increase. That is, if one explored a large sample of dams having no effect on mean water quality, the distribution would be 5%/90%/5%. If, on the other hand, there is a difference, other percentages would appear for the increase and decreasing categories - say 10% or 20%.

The statistical approach is straightforward. The mean of a sample from any distribution tends to be normal by the Central Limit Theorem. The differences of two means, in this case, the mean upstream and the mean downstream water quality, also tend to be normal because sums and differences of normal variates are themselves normal. The variance, or square of the standard error of the mean difference is the sum of the variances associated with the individual means, each computed with their respective sample sizes (Hoel, 1951). With this information, the hypotheses are that:

- the positive difference of means is significant, or
- the negative difference of means is significant.

The hypotheses are accepted with 95 percent confidence if a positive difference is greater than 1.65 times the standard error of the mean difference or an absolute value of a negative difference is greater than the same product.

---

[1]Applying a 95% confidence interval for a "one tailed" test on each end of the distribution of the mean difference.

**Findings.**

There are 1701 large nonpower dams having over 10,000 acre•feet of storage. Twenty-five percent, or less, of the random samples of nonpower dams have water quality data both upstream and downstream of the impoundment. Tallies for those dams having water quality data are found in Appendix D.

There are 66,030 "small" dams having less than 10,000 acre•feet of normal pool volume comprising 96.8 percent of the population of Corps of Engineers dams. Of the 40 small random dams in the sample, only 5 had some form of water quality data. Therefore, there is very little water quality monitoring evidence to indicate the effects of small impoundments. What monitoring results there are, as well as descriptive and site specific information on southeastern small dams are presented in Appendix E.

The large power dams have installed power and over 10,000 acre•feet of storage. The results of comparing water quality means are presented in Table III-4. Over half the random sample of dams have data on temperature, dissolved oxygen, phosphorus, and TKN both upstream and downstream of the impoundment. Reasonable bounds can be stated for most of the parameters.

Table III-4.
Upstream/Downstream Water Quality Changes
For Large Power Dams.

| Parameter | Dams Lacking Necessary Data | Dams with Upstream and Downstream Data | | | |
|---|---|---|---|---|---|
| | | Total Having Data | Significant Increase | Significant Decrease | Insignificant** |
| Temperature | 11 | 29 | 11 | 5 | 13 |
| Dissolved Oxygen | 11 | 29 | 8 | 9 | 12 |
| Dissolved Oxygen* | 11 | 29 | 6 | 9 | 14 |
| Iron | 23 | 17 | 4 | 3 | 10 |
| Manganese | 30 | 10 | 0 | 1 | 9 |
| Phosphorus | 16 | 24 | 5 | 12 | 7 |
| TKN | 17 | 23 | 4 | 10 | 9 |
| Total Nitrogen | 31 | 9 | 1 | 2 | 6 |

* nearest station to dam
** indicates no change in water quality

An impoundment can either increase or decrease tailwater temperatures depending upon the level of the outlets. Surface outlets would release warm surface waters and low-level outlets could release colder hypolimnetic waters of stratified impoundments. Of the sample of 40 random large power dams, between 27.5 percent and 55 percent increase the annual average downstream temperature and between 12.5 percent and 40 percent decrease annual average downstream temperatures. For large nonpower and small dams, the data are too limited to provide reasonable effect estimates.

For hypolimnetic low-level releases, the dissolved oxygen may be lower than upstream with corresponding increases in soluble iron and manganese. Of the sample of 40 random large power dams, between 22.5 percent and 50 percent show significant annual decreases in dissolved oxygen. This effect is evidenced in the annual data; the numbers of significant water quality changes would possibly be higher for a comparison of seasonal means.

## PHOSPHORUS ENRICHMENT ANALYSIS

This analysis is oriented to determination of the extent of possible nutrient enrichment of impoundments. Over enrichment can lead to water quality effects. This analysis is the fourth of four major analytical efforts undertaken for this report. The approach is to estimate the average phosphorus concentration in the pool. Then, a simple tally is made to determine the numbers of dams having average concentrations exceeding the EPA suggested "Gold Book" guidance value of 0.025 mg/l (USEPA, 1986). There are several points to consider in evaluation of this method:

- The EPA guidance value is "suggested" and not a standard.
- Phosphorus enrichment is only an indication of eutrophication, although 50 to 90 percent of the variation of other trophic state measurements are predicted with water column phosphorus concentrations (Sobotka and Company, Inc., 1986).
- The approach to "filling in" missing data uses Vollenweider's model discussed in Appendix C. It is an elementary approach, but it works with the available information and is appropriate for screening.
- Phosphorus data on large power dams are relatively plentiful, but not for other dams. Thus, the results pertain to large power dams. Data gathered for large nonpower and small dams appear in Appendices D and E, respectively.

**Relationship of Phosphorus Enrichment and Eutrophication.**

Ambient phosphorus concentrations do not measure eutrophication although they do indicate a potential for eutrophication. EPA recognized that a number of specific exceptions can occur which may reduce the threat of phosphorus as a contributor to lake eutrophication:

- naturally occurring phenomena may limit the development of plant nuisances;
- technological or cost-effective limitations may help control introduced pollutants;
- waters may be highly laden with natural silts or colors that reduce the penetration of sunlight needed for plant photosynthesis;
- waters may have no history of plant problems due to various morphometric features such as steep banks, great depth, and substantial flows;
- in some waters, nutrients other than phosphorus are limiting to plant growth; the level and nature of such limiting nutrient would not be expected to increase to an extent that would influence eutrophication; and
- in some waters, phosphorus control cannot be sufficiently effective under present technology to make phosphorus the limiting nutrient.

A brief analysis was performed on the nitrogen and phosphorus data to confirm the hypothesis that phosphorus enrichment is a reasonable screening indicator for overall potential impoundment enrichment. This was accomplished by examining total nitrogen concentrations, total phosphorus concentrations, and the N:P ratio for ten sites with both phosphorus and nitrogen data for the pool as shown in Table III-5.

The assessment of nitrogen versus phosphorus limitation is often performed using the N:P ratio (USEPA, 1985; USEPA, 1978b). If this ratio is greater than a given value, the water body is considered to be phosphorus limited. The appropriate ratio is dependent on the types of algae and macrophyte growth that may occur and usually ranges between 7 and 15 (USEPA, 1985; USEPA, 1978b). Five of ten sites exhibit N:P ratios greater than or equal to 15, and seven of ten sites show ratios greater than or equal to 7 suggesting phosphorus limiting conditions.

Table III-5
Selected Summary of Nitrogen and Phosphorus in the Pool
("Yes" implies enriched levels)

| Site | N:P Ratio | P > 0.025 mg/l* | N > 0.375 mg/l** |
|---|---|---|---|
| AK00001 | 32. | No (0.01) | No (0.32) |
| AR00174 | 3. | Yes (0.03) | No (0.09) |
| CA00813 | 4. | Yes (0.22) | Yes (0.84) |
| CA10162 | 37. | No (0.01) | No (0.37) |
| GA03742 | 7. | Yes (0.08) | Yes (0.59) |
| ID00223 | 4. | Yes (0.09) | No (0.36) |
| KY03048 | 16. | Yes (0.06) | Yes (0.95) |
| MN00653 | 16. | Yes (0.04) | Yes (0.66) |
| PA00924 | 43. | Yes (0.08) | Yes (3.46) |
| TN03702 | 12. | Yes (0.06) | Yes (0.70) |

* Phosphorus measurements may be made down to 0.01 mg/l using the single reagent method and 0.001 mg/l using the automated colorimetric ascorbic acid reduction method (USEPA, 1974).

** A concentration of 0.375 mg/l (as **N**) corresponds to a balanced condition of nitrogen and phosphorus with phosphorus at the 0.025 mg/l criterion level using an N:P ratio of 15:1.

The phosphorus data in Table III-5 show that eight of ten sites are labeled as "phosphorus enriched" based on the 0.025 mg/l guidance value, yet only five to seven are estimated to be phosphorus limiting. However, the thrust of this analysis is to develop an indicator of enrichment. Examination of the corresponding nitrogen data suggests that high phosphorus concentrations may indicate enrichment whether or not phosphorus concentrations are limiting. For example, the site CA00813 exhibits extremely high nitrogen as well as phosphorus concentrations, but an N:P ratio of only 4. Therefore, the indication of phosphorus enrichment was suggestive of overall enrichment in spite of the fact that phosphorus is not limiting.

Furthermore, the practical consideration is how to achieve nutrient reduction for situations that are enriched. It appears, based on point source control, that phosphorus reduction is much less expensive than nitrogen reduction. Thus, it is economically possible to make a previously nitrogen limiting situation into a phosphorus limiting case and to achieve enrichment control. In other words, phosphorus is more cost effective to remove than nitrogen. It makes operational sense to judge enrichment with high phosphorus levels since it may be feasible to reduce them and make phosphorus either become the (or become the more) limiting nutrient.

In sum, there are two sites (AR00074 and ID00223) of the ten which show enriched levels of phosphorus combined with lower levels of nitrogen as defined in Table III-5; and the nitrogen level for site ID00223 is only slightly below the specified nitrogen threshold (0.36 mg/l versus

0.375 mg/l). Therefore, these data support the use of phosphorus enrichment as a key indicator of eutrophication while at the same time demonstrating the importance of qualifying its use as an indicator. Note, however, that since these data are not statistically representative, these data cannot be used to quantify error bounds.

Nutrients in the water column and eutrophication are related and this linkage is discussed in the chapter on generic effects. TVA evaluated the trophic status of their reservoirs (TVA, 1983). They mention that eutrophication, from the Greek word for "well fed," refers to progressive fertilization of a water body and the changes in water quality that result. Natural eutrophication, over geologic time spans of thousands of years, is a normal process of aging. During lake aging, plant biomass accumulates until rooted aquatic plants cover the entire bottom of a lake and the basin fills with organic and inorganic sediments. Rivers and man-made reservoirs with short retention times do not age in the same way as lakes, but added nutrients may increase their biological productivity to levels traditionally identified as "eutrophic."

TVA also recommends that "Evaluation of TVA reservoirs based on trophic state indices devised for classification of natural lakes should be avoided", and further states that "Models predicting in-lake phosphorus concentrations from phosphorus loads assuming steady state conditions and continuous stirred tank reactor behavior are inappropriate for the evaluation of most TVA reservoirs and should be avoided."

However, a report performed under contract to EPA (Sobotka and Company, 1986) points out the generally acknowledged understanding that "...ambient concentrations of phosphorus bear a strong but not perfect relationship to eutrophication response...algal growth, water transparency, DO depletion, species diversity, etc." The report points out that correlation studies of cross-sectional samples of more sophisticated trophic state measurements and ambient phosphorus concentration are on the order of 0.5 to 0.9. This indicates a percentage of explained variation, $R^2$, of 25 percent to 81 percent. The same report then states the operational conclusion:

> "In our view, this smallish imperfection in the relationship between **P** concentration and ultimate water quality concerns is a reasonable price to pay in exchange for the advantages in implementability of an ambient **P** standard. An ambient **P** standard is much easier to translate into permit limits and other control decisions than water quality standards expressed in other items -- as narratives, as chlorophyll limits, or as trophic states."

The 1986 EPA "Gold Book" on quality criteria for water presents a rationale to support guidance for ambient phosphorus. To prevent the development of biological nuisances and to control accelerated or cultural eutrophication, a suggested phosphorus guidance value for lakes and reservoirs is published by EPA at 0.025 mg/l. Thus, the simplest model or approach is to use 0.025 mg/l as a threshold level. If ambient phosphorus exceeds 0.025 eutrophication is suspected, and, in fact, EPA is considering "control" and regulatory options to cut levels back as evidenced by their "Gold Book" suggestions. From a pragmatic screening standpoint, one can assign measured or predicted reservoir phosphorus concentrations of greater than 0.025 to indicate either potential or actual eutrophic condition.

**TVA and CE Results.**

There are reservations about using the Vollenweider model, or similar models, for control decisions. However, it is instructive to review TVA trophic status data (TVA, 1987a) for several TVA tributary reservoirs reproduced in Table III-6. The Vollenweider predictions calculated by TVA are based on a $V_s$ = 10 meters/year, apparent settling velocity. The uncorrected Vollenweider model used by TVA uniformly overestimates phosphorus cncentrations. A corrected model is discussed in the next section.

The square of the correlation coefficient, $R^2$, of these 11 samples, between Vollenweider prediction and measurement, is 44 percent. This is a significant $R^2$, but probably not strong enough to make site specific decisions. However, $R^2$ is sufficient to provide credibility to the next section of this chapter.

Table III-6.
TVA Trophic Status Data.

| Site | Phosphorus Concentration (mg/l) Vollenweider | Measured |
|---|---|---|
| Blue Ridge | .015 | .007 |
| Boone | .063 | .022 |
| Chatuga | .017 | .009 |
| Cherokee | .148 | .021 |
| Douglas | .062 | .024 |
| Fontana | .061 | .008 |
| Hiawassee | .022 | .010 |
| Norris | .032 | .007 |
| South Holston | .029 | .008 |
| Tims Ford | .017 | .009 |
| Watauga | .044 | .006 |

Kennedy and Gaugush (1987) also report data for phosphorus, nitrogen, and chlorophyll-*a* taken from STORET for 47 southeastern Corps of Engineers reservoirs and the same parameters for 299 reservoirs Corps-wide taken from Walker (1981). These data for the growing season (April-September) in the mixed layer (0-3 meters) are reproduced in Table III-7. Kennedy and Gaugush concluded that southeastern reservoirs are typical of Corps reservoirs in terms of phosphorus and chlorophyll-a, but much different with respect to nitrogen. Kennedy and Gaugush suggest that reservoirs in the southeast may experience nitrogen limitation of primary production.

Table III-7
Summary Statistics for Total Phosphorus, Total Nitrogen, and Chlorophyll-a in the Mixed Layer (0-3 m) During the Growing Season (April through September).

| Variable (mg/l) | Mean (47 Southeastern Reservoirs) | Mean (299 Corps-wide Reservoirs)* |
|---|---|---|
| TP | 0.044 | 0.048 |
| TN | 0.372 | 1.00 |
| CHL-a | 0.0093 | 0.0093 |

* "Corps-wide" refers to a Corps reservoir data set described in Walker (1981).

**Phosphorus Retention Regression Model**.

Of the 80 dams in the random sample with 10,000 acre•feet or more, 22 have average phosphorus data for inflows and pool concentrations that are used in a correlation analysis. Small dam sites were excluded because none of the sample had upstream and pool phosphorus data. The analysis proceeds through the following steps:

- The inflow phosphorus is utilized with the Vollenweider model to make a prediction of pool concentrations. The apparent settling velocity, $V_s$ = 10 meters/year, is utilized.
- The 22 predictions are compared to the 22 observations.
- The observed values are analyzed in a least squares regression analysis as a linear function of the Vollenweider calculated values. The line is constrained to pass through the origin.

The data for this analysis are found in Appendix B and the results are presented in Figure III-7. The correlation between observed and calculated data is 0.72 which implies a significant $R^2$ of 0.52. This correlation is slightly better than the TVA results presented in the previous section. The slope of the regression line is 0.65 indicating that Vollenweider estimates, that utilize $V_s$=10, make a high prediction of pool concentration. Thus, if one reduces the Vollenweider prediction by 35 percent (multiply by 0.65), one obtains a "corrected" least squares estimator of the phosphorus in the pool.

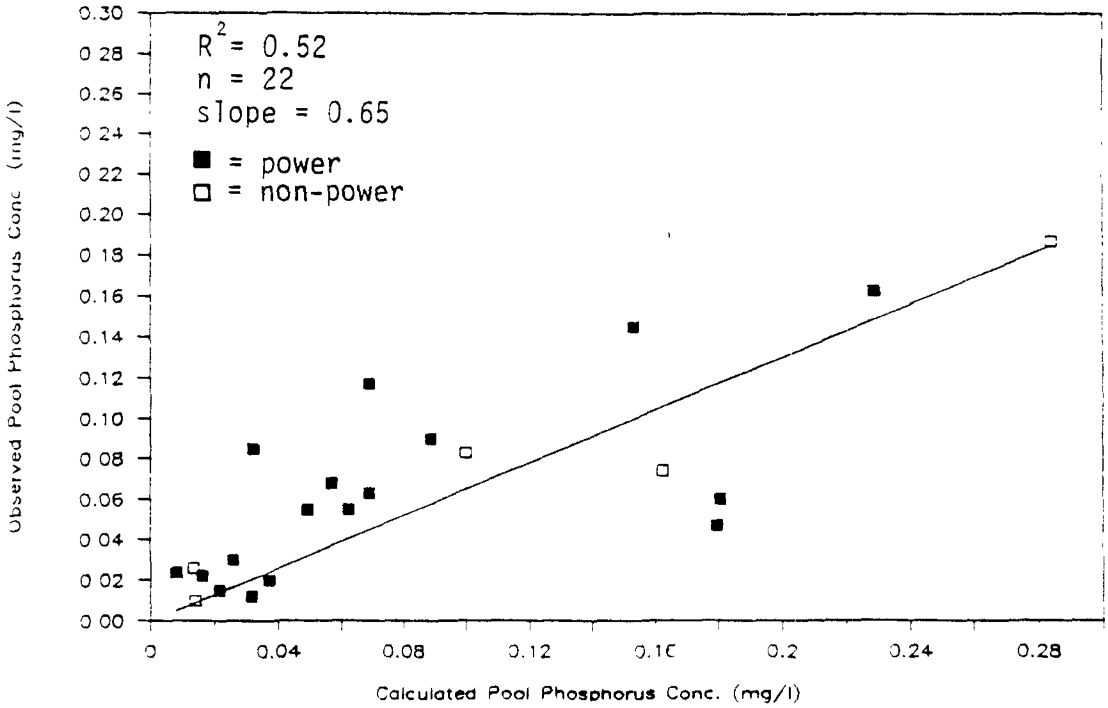



Figure III-7. Vollenweider Model Performance.

**Findings**.

An estimate of nutrient enrichment potential derived from the random sample of dams is presented. The estimate is based on average phosphorus data in the impoundment pool, or lacking actual data, from the "corrected" least squares estimator of the phosphorus in the pool discussed above.

The actual data, and the "corrected" estimates which fill in missing in-pool values when upstream values exist, are presented in Appendix B. Even using the regressions for large nonpower dams, insufficient data were available, for a representative analysis of the large nonpower dams sample, therefore, only data for large power dams are summarized in Table III-8. Data for large nonpower dams can be found in Appendix D. Using the suggested EPA guidance value of 0.025 mg/l phosphorus in the water column for the sample of large power dams, between 57.5 percent and 77.5 percent are phosphorus enriched.

Table III-8.
Phosphorus Enrichment Results
for Large Power Dams

| Data Source | No Phos. Data | $P < 0.025$ | $P > 0.025$ |
|---|---|---|---|
| | Number of Dams | | |
| Observed Pool Data | - | 6 | 16 |
| "Corrected" Estimate | - | 3 | 7 |
| Missing Data | 8 | - | - |
| Total | 8 | 9 | 23 |

# IV. CASE STUDIES

## INTRODUCTION

Fifteen case studies have been selected for presentation in this chapter as a means of describing some water quality effects resulting from the impoundment of water and methods available for mitigating negative effects. The selection of case study sites was meant to enhance understanding by providing specific examples of situations which have occurred in the past and not to be representative of the distribution of effects. The case studies also illustrate the mitigation action which has been taken by the responsible agencies.

Case study suggestions and selections were made during the course of several meetings with interested Federal agencies, including the Bureau of Reclamation (BR), the Army Corps of Engineers, and the Tennessee Valley Authority. Through their knowledge of particular sites, the set of case studies was developed and the original text for this report was provided. The text was edited only to place each case study in a common format. Therefore, the information supplied reflects the assessment of the respective agency (BR, 1987b; CE, 1987; TVA, 1987b).

The case studies are distributed throughout the country, as shown in Figure IV-1, to show the effects that climate and location may have on water quality conditions. For example, Lake Casitas is located in southern California where almost all of the precipitation occurs in the winter. This results in a highly stable stratified condition, leading to an anoxic hypolimnion in the summer. The climate of an area will also affect the period of stratification and occurrence of mixing. For example, in southern states longer summers result in a longer period of stratification.

Physical characteristics of a reservoir, including volume, length, depth, surface, and shoreline length, may all be related to the observed water quality in a reservoir or downstream. For example, reservoirs with a large storage area in relation to drainage area will have a long detention time, with a resulting increased degree of settling of sediments and organic matter. This may result in increased decomposition in the hypolimnion and a possible increased tendency towards eutrophication. The depth of the reservoir will affect annual heat budgets and the impoundment's resistance to mixing. Shoreline length gives an indication of the extent of the littoral zone (the interface between the land of the drainage basin and the open water of the lake).

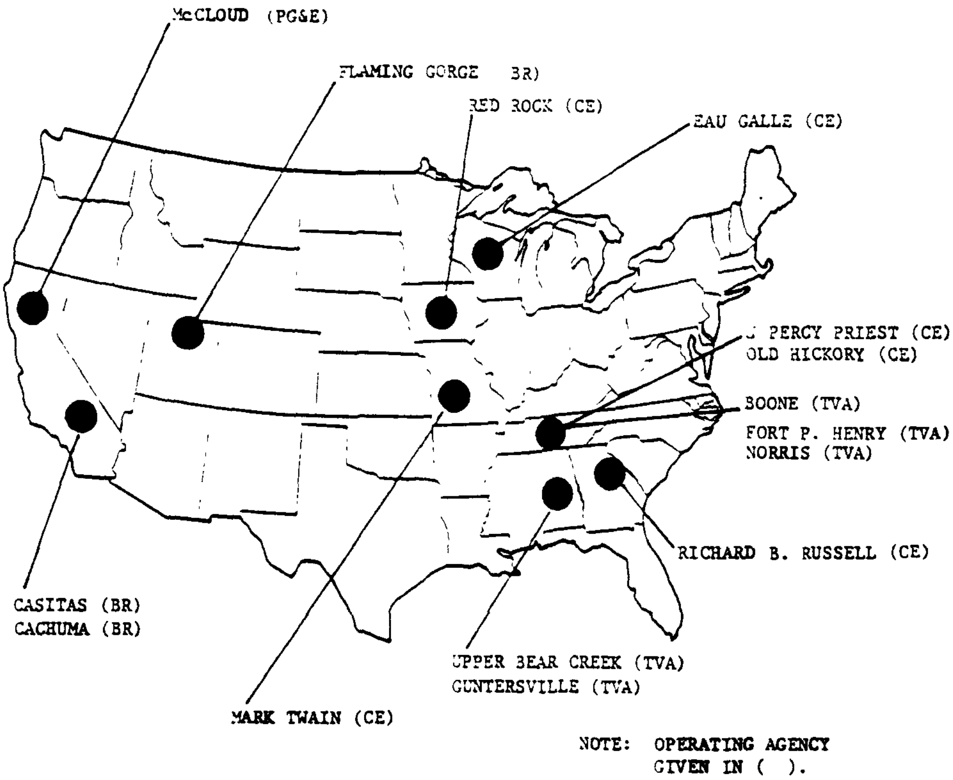



Figure IV-1
Location and Name of Case Study Impoundments

The littoral zone is often a very productive habitat and also contributes organic detritus to the aquatic system. Table IV-1 lists each of these characteristics along with the name of the impounded river, the major purposes, and the year the impoundment was filled.

Impoundment date is also important because water quality conditions often change with time. For example, Richard B. Russell Lake presently has low DO conditions in the hypolimnion caused by the recent inundation of a forested area to form the lake. This condition should improve as the reservoir ages. The newer reservoirs, such as Casitas Lake, were designed with multilevel intakes and other measures as a means to mitigate potential water quality problems. Since reservoirs act as sinks for substances as they age, sediment, organic matter, metals and other pollutants entering the reservoir will accumulate in the benthos and, if resuspended, can have a negative effect on water quality.

The uses of a reservoir may affect the water quality conditions in the tailwater since they will be a major determinant of the method of withdrawal and frequency of flow release. For example, the water may be released and aerated by being discharged over the dam spillway or constrained in turbines and taken from deeper waters for power production. The uses may also constrain the type of mitigation measures that can be implemented.

Table IV-2 gives an overview of the major water quality effects found in the case study reservoirs, while Table IV-3 presents the mitigative measures either planned or implemented. In the narrative that follows, the reservoirs are grouped by the major type of water quality effect. The major types of effects include: low hypolimnetic DO, increased iron and manganese, eutrophication, sediment movement, flow regulation, reaeration denial, thermal changes, as well as neutral or positive effects. Several of the case studies exhibit multiple water quality effects. The categorical listing is intended merely to highlight one prominent effect.

## LOW DISSOLVED OXYGEN AND/OR INCREASED IRON AND MANGANESE

### J. Percy Priest Lake and Dam

Operating Agency: Corps of Engineers

Location. J. Percy Priest Dam and Lake are located at mile 6.8 on the Stones River within the metropolitan area of Nashville, Tennessee. Discharges from the dam flow into the Cumberland River at mile 205.9, which is about 15 river miles upstream of the inner city area.

Principal Features. J. Percy Priest Lake is approximately 211,000 feet long and has a maximum depth of 103 feet. The summer recreation pool level has a volume of 391,900 acre•feet, a surface area of 14,200 acres, and 213 miles of shoreline. The drainage area feeding the lake covers 571,000 acres. The dam was completed in 1967.

Uses. The major uses of the lake and dam are flood control, hydropower production, and recreation. The powerplant contains one turbine with a capacity of 28,000 kW. The lake and the reach of the Stones River downstream of the dam are classified by the state for all stream uses, including: domestic water supply, industrial water supply, fish and aquatic life, recreation, irrigation and livestock watering, and wildlife habitat.

Water Quality Conditions. J. Percy Priest Lake is classified as eutrophic as a result of nutrient loads directly attributable to upstream land use activities. High nutrient concentrations occur particularly during the growing season and result in heavy algal blooms, and other plant growth, which occasionally impair water uses such as water supply and recreation. The lake also exhibits other water quality characteristics typical of highly productive lake systems.

Thermal stratification and the decay of organic material results in an anoxic hypolimnion. High concentrations of dissolved iron and manganese and the production of hydrogen sulfide result, causing the water to have the appearance of black ink and a strong rotten egg odor.

During power production, water withdrawn from the lower layers of the reservoir and discharged through the turbine becomes aerated while flowing through the tailwater. This reoxidation causes the dissolved

Table IV-1
Comparison of Principal Features of Case Study Impoundments/Dams

| Impoundment/ Dam | River Impounded | Major Use(s) | Active Storage Vol. (acre·feet) | Length (feet) | Maximum Depth (feet) | Surface Area (acres) | Shoreline Length (miles) | Drainage Area (acres) | Year Filled |
|---|---|---|---|---|---|---|---|---|---|
| Boone Reservoir & Dam, TN | South Fork Holston River | F,N, H | 189,100 | 91,900 | 122 | 4,310 | 122 | 1,180,000 | 1952 |
| Lake Cachuma & Bradbury Dam, CA | Santa Ynez River | W | 202,000 | n.p. | 190 | 3,100 | 42 | 267,000 | 1953 |
| Lake Casitas & Casitas Dam, CA | Coyote Creek | W | 251,000 | n.p. | 260 | 2,700 | 31 | 69,100 | 1959 |
| Eau Galle Lake and Dam, WI | Eau Galle River | F,R | 1,500 | 3,300 | 30 | 150 | 2.5 | 41,000 | 1969 |
| Flaming Gorge Reservoir and Dam, UT | Green River | H | 3,516,000 | 475,000 | 440 | 42,000 | 375 | 11,300,000 | 1962 |
| Fort P. Henry Reservoir and Dam, TN | South Fork Holston River | H | 26,900 | 54,900 | 80 | 872 | 37 | 1,220,000 | 1953 |
| Guntersville Reservoir and Dam AL & TN | Tennessee River | F,N, H | 1,020,000 | 401,000 | 60 | 67,900 | 949 | 15,600,000 | 1939 |
| J. Percy Priest Lake and Dam, TN | Stones River | F,H, R | 391,900 | 211,000 | 103 | 14,200 | 213 | 571,000 | 1967 |

n.p. = not provided by operating agency

KEY: F - Flood Control; N - Navigation; H - Hydropower; W - Water Supply; R - Recreation

Table IV-1 (con't)
Comparison of Principal Features of Case Study Impoundments/Dams

| Impoundment/ Dam | River Impounded | Major Use(s) | Active Storage Vol. (acre·feet) | Length (feet) | Maximum Depth (feet) | Surface Area (acres) | Shoreline Length (miles) | Drainage Area (acres) | Year Filled |
|---|---|---|---|---|---|---|---|---|---|
| Mark Twain Lake and Clarence Cannon Dam, MO. | Salt River | F,H, W,R | 457,000 | 132,000 | n.p. | 18,600 | 285 | 1,470,000 | Mark Twain n.p. |
| McCloud Reservoir and Dam, CA | McCloud River | H | 35,200 | n.p. | n.p. | 520 | n.p. | 269,000 | 1965 |
| Norris Reservoir and Dam, TN | Clinch River | F,N, H | 2,040,000 | 385,000 | 200 | 34,200 | 750 | 1,860,000 | 1937 |
| Old Hickory Lake & Lock and Dam, TN | Cumberland River | H,N F,R | 420,000 | 528,000 | 70 | 22,500 | n.p. | 898,000 | 1954 |
| Lake Red Rock and Red Rock Dam, IA | Des Moines River | F,R | 90,000 | 42,200 | n.p. | 6,300 | n.p. | 4,160,000 | 1969 |
| Richard B. Russell Lake and Dam, GA | Savannah River | H,F, W,R | 1,030,000 | n.p. | 150 | 26,700 | 550 | n.p. | 1984 |
| Upper Bear Creek Res. and Dam, AL | Upper Bear Creek | R,W | 37,400 | 37,000 | 70 | n.p. | 100 | 72,300 | 1980 |

n.p. = not provided by operating agency

KEY: F - Flood Control, N - Navigation, H - Hydropower, W - Water Supply, R - Recreation

Table IV-2
Case Study Profiles: Principal Effects of Dam on Water Quality

| SITE | Stratification | Low Hypolimentic DO | Increased Fe & Mn | Increased $H_2S$ | Denitrification | Thermal Changes | Eutrophication | Gaseous Supersatn | Sediment Movement | Flow Regulation | Reaeration Denial | Fish Entrainment | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boone Reservoir & Dam, TN | √ | √ | | | | | √ | | | | | | √ |
| Lake Cachuma & Bradbury Dam, CA | ● | ● | ● | ● | | | | | | | | | |
| Lake Casitas & Casitas Dam, CA | ● | ● | ● | ● | | | ● | | | | | | |
| Eau Galle Lake & Dam, WI | √ | √ | | | | | ● | | | | | | |
| Flaming Gorge Reservoir & Dam, UT | ● | ● | | | | ● | | | | | | | |
| Fort Patrick Henry Reservoir & Dam, TN | | | | | | | | | | ● | √ | | |
| Guntersville Reservoir & Dam, AL & TN | √ | √ | | | | | √ | | | | | | |
| J. Percy Priest Lake & Dam, TN | √ | √ | √ | √ | | | √ | | | √ | √ | | |
| Mark Twain Lake & Clarence Cannon Dam, MO | √ | √ | | | | | | | | √ | √ | | |
| McCloud Reservoir & Dam, CA | | | | | | | | | * | | | | |
| Norris Reservoir & Dam, TN | √ | √ | | | | | | | | ● | ● | | |

* McCloud reservoir improves tailwater turbidity conditions.

Key: √ - Currently a problem
● - Improved by Mitigation Measure

Table IV-2 (con't)
Case Study Profiles: Principal Effects of Dam on Water Quality

| SITE | Strati-fication | Low Hypo-limentic DO | Increased Fe & Mn | Increased $H_2S$ | Denitri-fication | Thermal Changes | Eutrophi-cation | Gaseous Supersatn | Sediment Movement | Flow Regulation | Reaeration Denial | Fish Entrainment | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Old Hickory Lake, Lock & Dam, TN | √ | √ | | | | | | | | | √ | | |
| Lake Red Rock & Red Rock Dam, IA | | | | | | | | | √ | | | | |
| Richard B. Russell Lake & Dam, GA | √ | ● | ● | | | | | | | | ● | | |
| Upper Bear Creek Resevoir & Dam, AL | ● | ● | ● | ● | | ● | | | | | | | |

Key: √ - Currently a problem
● - Improved by Mitigation Measure

Table IV-3
Case Study Profiles: Mitigation Measures.

| SITE | POOL MODIFICATIONS | | | | TAILWATER MODIFICATIONS | | | | OTHER MODIFICATIONS | | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Destratification | Aeration | Dredging | Other | Aeration | Selective Withdrawals | Habitat Improvement | Other | Operating Rules | NPS Control | |
| Boone Reservoir and Dam, TN | | | | | | | | | | √ | Pollutant reduction being developed. Bacterial, toxicity and sludge problems. |
| Lake Cachuma & Bradbury Dam, CA | √ | | | | | √ | | | | | Air injection system in hypolimnion - lower basin. |
| Lake Casitas & Casitas Dam, CA | √ | | | √ | | √ | | | | | Air injection in hypolimnion - destratification and aeration. Copper sulfate algal control. |
| Eau Galle Lake & Dam, WI | | | | √ | | | | | | | Hypolimnetic use of aluminum sulfate to control phosphorus. |
| Flaming Gorge Reservoir & Dam, UT | | | | | | √ | | | | | Selective withdrawals increase temperature of tailwaters. |
| Fort Patrick Henry Reservoir & Dam, TN | | | | | | | | | √ | | Increased pulsed flow to tailwaters. |
| Guntersville Reservoir & Dam, AL & TN | | P | | √ | | | | | | P | Herbicide treatments and grass carp used to control eutrophication. Sediment/nutrient controls planned. Sediment/removal and aeration planned. |
| J. Percy Priest Lake & Dam, TN | | P | | | | | | | √ | | Coordination of releases to increase flow in tailwater, and localized mixing to force withdrawal of surface water. |
| Mark Twain Lake & Clarence Cannon Dam, MO | | P | | | | | | | | | Destratification system planned. |
| McCloud Reservoir & Dam, CA | | | | | | | | | | | DO concentrations are above standards. Dam has little impact on temperature downstream. |
| Norris Reservoir & Dam, TN | | | | | √ | | √ | √ | | | Aeration system in turbine and flow reregulation weir in place. Increased stocking of fish and transplant of benthic fauna. |

Key: √ - Currently in place
P - Planned

Table IV-3 (con't)
Case Study Profiles: Mitigation Measures.

| SITE | POOL MODIFICATIONS | | | | TAILWATER MODIFICATIONS | | | | OTHER MODIFICATIONS | | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Destratification | Aeration | Dredging | Other | Aeration | Selective Withdrawals | Habitat Improvement | Other | Operating Rules | NPS Control | |
| Old Hickory Lake, Lock & Dam, TN | | | | | | | | | P | | Rescheduling of upstream storage operations planned to aviod low DO releases. |
| Lake Red Rock & Red Rock Dam, IA | | | | | | | | | P | | Studying a permanent increase in conservation pool level. |
| Richard B. Russell Lake & Dam, GA | | √ | | | | | | | | | Completion of generators increased fushing rate of reservoir. Hypolimnetic oxygen injection system installed. |
| Upper Bear Creek Resevoir & Dam, AL | √ | √ | | | | | | | | | Installed aeration system in hypolimnion in 1987 to increase DO and make less stable stratification conditions. |

Key: √ - Currently in place
P - Planned

iron and manganese to precipitate, staining downstream areas. Iron concentrations are reduced to low levels a short distance downstream. Manganese, however, is very persistent with effects evident some distance downstream. The manganese concentrations affect domestic and industrial water supplies, particularly under the anaerobic summer conditions.

Mitigation/Enhancement Measures. A mitigation measure that has been implemented is the coordination of releases with another dam. When discharges are required (for power production) from J. Percy Priest Lake during the stratification period, releases are coordinated with releases from Old Hickory Lock and Dam on the mainstem of the Cumberland River so that manganese concentrations will have a lesser effect on water treatment plants downstream.

Another measure selected for testing in 1987 is the installation of pumps in the forebay, upstream of the penstock, to cause localized mixing. This measure will force entrainment of surface water into the withdrawal zone of the turbine intake. Thus, a high percentage of high quality surface water will enter the penstock and, in effect, prevent or reduce the percentage withdrawal of the low quality waters within the hypolimnion.

**Old Hickory Lake, Lock, and Dam**
Operating Agency: Corps of Engineers

Location. Old Hickory Lake, Lock, and Dam are located at mile 216.2 on the Cumberland River in Davidson and Sumner Counties, Tennessee, about 25 river miles upstream of Nashville, Tennessee.

Principal Features. The reservoir was completed in 1954. The lake extends almost 100 miles upstream to Cordell Hill, at river mile 313.5, and has a maximum depth of 70 feet. The surface area of the lake is 22,500 acres and the volume is 420,000 acre•feet. The drainage area is 898,000 acres below upstream dams. There are several large embayments covering 5,000 acres in the downstream portion of the reservoir that are fairly isolated from the main channel flow. Flows to the lake are regulated by three upstream tributary storage reservoirs. The reservoir is generally confined to the old river channel and is very narrow and serpentine, with an average width of 1,500 feet, excluding embayments.

Uses. The main uses of the dam and lake are hydropower production and provision of navigation upstream to the Cordell Hull Lock and Dam. They also serve for flood control, recreation, and water quality. The reach of the Cumberland River downstream of Old Hickory is classified for public water supply and fish and aquatic life, and has a DO standard of 5 mg/l.

Water Quality Conditions. Analysis of data collected by the Corps of Engineers shows that Old Hickory may be thermally stratified from April or May to September. Dissolved oxygen concentrations during this period become reduced in the downstream forebay of the lake as well as in the releases to the tailwater. These conditions are most severe during periods of drought or low stream flow.

Water quality routing studies have shown that inflows from one of the upstream reservoirs, Cordell Hull Dam, are cooler and, therefore, are routed beneath the epilimnion during stratification. They are subsequently released in the tailwaters downstream. During times of drought or low flow, such as June through August, these inflows are reduced and the retention time in the hypolimnion is increased, lowering DO concentrations in the releases of Old Hickory. A minimum observed DO concentration of 2.1 mg/l occurred in August-September 1975. Flows during this period were unusually low due primarily to changes in discharges from controlled releases upstream. Seasonal drought conditions in the lake also contributed to these low DO values.

Mitigation/Enhancement Measures. Since Old Hickory Lock and Dam are operated for navigation and hydropower generation, the pool elevation is maintained within a tolerance of a few feet, in accordance with the project water control plan. This regular operation is maintained in concert with the discharges of dams upstream whose operations are also specified by project water control plans. The DO release problems associated with this system can be mitigated only if flows resulting from the projects can be accurately forecast in time to reschedule operations.

The need for a predictive capability of flows and their effects led to the development of a DO routing model between the uppermost storage project, Wolf Creek, and Old Hickory Dam. Modeling results are used to evaluate potential DO problems in the releases from Old Hickory Dam and to test various operational changes which might be required to avoid low DO concentrations. There is some flexibility in the operations of the upstream storage impoundments. Simulations of these operations suggest that a spring target allocation for storage in the impoundments upstream will provide water in sufficient quantity for flows through Old Hickory Lake during the summer stratification period. Other more detailed models are under development which will be used to evaluate the effects of particular point and nonpoint source discharges or in other situations where more realistic and detailed simulations of reservoir dynamics are required.

**Richard B. Russell Lake and Dam**
Operating Agency: Corps of Engineers

Location. Richard B. Russell Dam is located on the Savannah River at river mile 275 Elberton, Georgia, on the Georgia-South Carolina border. Two other Corps of Engineers reservoirs, Clarks Hill Lake and Hartwell Lake, are located immediately below and above Richard B. Russell Lake, respectively.

Principal Features. Richard B. Russell Lake has a surface area of 26,700 acres, a volume of 1,030,000 acre•feet, and a shoreline length of 550 miles. Mean and maximum depths are 38 and 150 feet, respectively, with a theoretical hydraulic residence time of 102 days. The dam was completed in 1984, but work on the dam and powerhouse, including the installation of four turbines, will continue until late 1989. The major inflow to the lake is the Savannah River, which is regulated immediately upstream by the operation of Hartwell Dam. Two large embayments were formed near mid-lake by the flooding of Rocky River to the east and Beaverdam Creek to the west.

Uses. Richard B. Russell Dam and Lake were authorized by the Flood Control Act of 1966 to provide power generation, incidental flood control, recreation, streamflow regulation, and water supply on the Savannah River. The installation of four reversible turbines for pumped storage operation will continue until late 1989. Current operation allows for power generation using four conventional turbines rated at 75 MW each. When completed, the powerhouse will have a total generating capacity of 600 MW. The dam is currently operated to meet peak power demand. Water from the Rocky River embayment also is the primary source of drinking water for the city of Abbeville, South Carolina. Dissolved oxygen standards require a minimum concentration of 6.0 mg/l in the tailwaters.

Water Quality Conditions. Water quality conditions in the lake have changed markedly since its impoundment. During the initial stages of the filling process, water quality conditions were strongly influenced by the inundation and subsequent decomposition of terrestrial vegetation, detritus, and organic materials contained in flooded soils. Nearly 9,000 acres of forested area were inundated during filling, resulting in the inundation of an estimated 550,000 metric tons green weight of standing vegetation and 5,100 metric tons of litter and detritus. While standing vegetation was determined to have minimal direct impacts on water quality, the decomposition of litter and detritus has had a pronounced impact, particularly with respect to DO concentrations in the bottom waters. Dissolved oxygen concentrations in bottom waters were severely depressed during the summer of 1984, and elevated concentrations of iron and manganese prevented the testing of turbines due to downstream water quality impacts. Also during 1984, powerhouse construction necessitated the release of water through tainter gates. This operational scheme reduced flushing of the hypolimnion, contributing to the accumulation of poor quality hypolimnetic waters. Following completion of the four conventional generators, releases were made from the lower portion of the water column. This greatly reduced the residence time of hypolimnetic waters and increased flushing. Inflows from Hartwell Lake were observed to enter Richard B. Russell Lake as an interflowing density current, which further increased flushing of deeper strata.

Water quality conditions were also impaired in the two major tributaries. Anoxic conditions developed in near-bottom waters by late March and iron and manganese concentrations began to increase. By early June much of the water column in each embayment was anoxic and elevated concentrations of soluble nutrients and iron and manganese were recorded. These conditions persisted until turnover in mid-November. On one occasion during summer stratification, the withdrawal of anoxic hypolimnetic water form the Rocky River embayment resulted in the short-term closure of the Abbeville water treatment facility until the relocation of the intake to a higher elevation was completed.

During 1985, the decomposition of litter and detritus accounted for approximately 60 percent of the total hypolimnetic oxygen demand. However, field and laboratory studies indicate that as organic materials are decomposed, oxygen demand should decrease by approximately 70 percent by 1988. These declines may have accounted for the less severe water quality conditions observed during 1986 and 1987.

During the summer stratification of 1985 through 1987, water quality conditions in the main portion of the reservoir greatly improved. These changes are related to the following: decreases in the quantity of labile terrestrial organic matter, changes in flow patterns in the lake, and operation of an oxygen injection system in the forebay. Improvements in the two major impoundments were far less pronounced, suggesting the importance of changes in flow patterns in influencing water quality conditions in the main portion of the reservoir.

Mitigation/Enhancement Measures. An oxygen injection system was designed and installed in Richard B. Russell Lake for the purpose of maintaining a minimum DO concentration of 6 mg/l in the tailwater. This is the DO standard for the tailwater and is based on the habitat requirements of the fishery in the upper reaches of Clarks Hill Lake. The injection system is composed of two independent components. A pulse component, consisting of eight diffuser lines, is oriented perpendicular to the intake section of the dam and is located approximately 10 to 16 feet above bottom grade. This component of the injection system provides additional oxygen injection capability during generation and is capable of delivering oxygen at a maximum rate of 80 tons/day. The second component was designed for continuous injection of oxygen at rates up to 100 tons/day, and is located approximately 1 mile upstream from the dam. During the summer stratified period, liquid oxygen is transported to the site, evaporated, and delivered to the diffuser system through a system of pipes.

Depending on conditions in the lake and tailwater, the system is generally operated from early April until mid to late November. Injection rates are varied periodically to insure adequate and economical operation by routine field monitoring and through the use of a numerical model. To date, the system has been operated successfully and problem conditions have not been observed in the tailwater. The system has also led to significant increases in the average summer oxygen concentration of bottom waters in areas immediately upstream from the dam.

**Upper Bear Creek Reservoir and Dam**

Operating Agency: Tennessee Valley Authority

Location. Upper Bear Creek Reservoir and Dam are located on Upper Bear Creek in northwestern Alabama in Marion County.

Principal Features. The reservoir is 37,000 feet long, with an average volume of 37,400 acre•feet, and a maximum depth of 70 feet. The total drainage area above the dam site is 72,300 acres.

Uses. The reservoir provides for fish and wildlife, recreation, shoreline development, and water quality control, and serves as a water supply for several communities. The reservoir was also designed to provide water for the weekend operation of the Bear Creek Floatway located downstream from the dam.

Water Quality Conditions. Low summer DO concentrations occur in the Upper Bear Creek Reservoir. Anoxic conditions in the lower depths of the reservoir provide a reducing environment, which results in the resolublization of iron, manganese, and sulfur present in the sediments and causing high concentrations in the water. One source of these constituents is believed to be upstream mining activities, but they can also occur naturally.

The water treatment plant that uses the reservoir as a water supply often struggles with the removal of the iron and manganese. When water is released from the lower depths of the reservoir, the iron and manganese oxidize and precipitate in the creek, leaving it highly stained, with large growths of iron bacteria and precipitates coating much of the aquatic life below the stream. Also, concentrations of hydrogen sulfide as high as 0.5 mg/l have been detected in the creek. Hydrogen sulfide in concentrations greater than 0.002 mg/l can be toxic to aquatic life. In 1986, iron and manganese concentrations of 6.9 mg/l and 3.6 mg/l, respectively, were measured immediately below the dam, while concentrations of approximately half these values were measured three miles below the dam.

Another effect of the dam occurs when the location of the release is changed. Water released from the surface overflow might be 10 to 15°C warmer than the water released from the low-level release. Changing the withdrawal point due to the decreasing reservoir elevation probably causes thermal shock to downstream aquatic organisms.

A biological study of Upper Bear Creek Reservoir was conducted by the State of Alabama during 1979 to 1983. The study concluded that benthic macroinvertebrate levels were adversely affected by the reservoir water quality. In addition, fish population data indicated a poor fishery exists in the reservoir.

Mitigation/Enhancement Measures. In 1987, a diffused aeration system was installed in the reservoir, consisting of four diffusers stretched across the old river channel. Compressors supply the air and are run continuously from about March to September. The aeration system significantly warmed the hypolimnion, rendering the reservoir stratification less stable. Dissolved oxygen levels have also increased. However, the reservoir has remained thermally and chemically stratified. This might be due in part to several compressor malfunctions which resulted in the operation of only two diffusers for several weeks. During the summer of 1987, all of the iron was converted to the oxidized form, but most of the manganese was still in the dissolved form. Both iron and manganese levels increased as the reservoir became more anoxic. However, the 1987 concentrations of iron and manganese were lower than they were before the aeration system was installed.

**Casitas Lake and Dam**
Operating Agency: Bureau of Reclamation

Location. Lake Casitas is located in southern California near Santa Barbara. The two main tributary inflows are Coyote Creek and the Robles-Casitas Diversion Canal.

Principal Features. The reservoir has an active capacity of 251,000 acre•feet, a maximum depth of 260 feet, a surface area of 2,700 acres, and 31 miles of shoreline. The reservoir was filled in 1959. The Coyote Creek watershed has a direct drainage basin of 21,100 acres and is former ranch land that is now managed for recreation and water quality control. The Robles-Casitas Diversion Canal brings in water from the Ventura River, which drains 48,000 acres. This indirect drainage basin includes numerous small holdings, large ranches, public domain land, and a population of about 10,000. Due to the climate of the area, the reservoir is typically filled during the winter rains, and then is drawn down steadily during the summer when there is little or no significant precipitation. The dam was originally designed with a multi-level intake to the outlet structure that allows selected strata to be withdrawn.

Uses. The Casitas Municipal Water District manages the lake primarily for water supply. Secondary water uses include irrigation and nonbody contact recreation.

Water Quality Conditions. From 1959 to 1967, water below about 60 feet from the surface and, at times, as little as 30 feet below the surface became anaerobic during the summer thermal stratification. Unacceptable concentrations of manganese and hydrogen sulfide accumulated in this anaerobic zone. At the same time, blooms of taste and odor-producing algae developed in the surface water. Under these extreme situations, attempts to use the multi-level intake to withdraw water from the narrow zone between the algal blooms and the anaerobic hypolimnion often failed.

Mitigation/Enhancement Measures. In 1968, a diffused air injection reaeration system was installed in the reservoir that injects compressed air into the hypolimnion through a series of diffusers that are positioned 80 to 100 feet from the bottom. The system has been refined over the years.

The reaeration eliminated the water quality problems caused by manganese and hydrogen sulfide accumulations in the hypolimnion. It is now possible to withdraw water from 100 feet or more below the surface during summer stratification, thus avoiding any taste and odor problems from surface algae. This, in turn, allowed a reduction in the number of copper sulfate applications needed to control algae. Aeration of the cooler depths of the lake during the summer months made possible the establishment of a "2-story fishery" with warm-water species, like bass, in the upper waters and rainbow trout in the deeper waters.

**Lake Cachuma and Bradbury Dam**
Operating Agency: Bureau of Reclamation

Location. Bradbury Dam is located on the Santa Ynez River near Ventura in southern California.

Principal Features. The reservoir has an active capacity of 202,000 acre•feet, a maximum depth of 190 feet, a surface area of 3,100 acres, and a 42-mile shoreline. The drainage area is 267,000 acres, with most of the drainage basin consisting of the Los Padres National Forest. Runoff is extremely variable from year to year, with almost all of the annual runoff concentrated in the winter months.

Uses. The major use of the reservoir is water supply. Most of the water districts withdraw their supplies from the upper end of Lake Cachuma through a multi-level selective withdrawal tower. However, the Santa Ynez River Water Conservation District (SYRWCD) withdraws its supply of water from the bottom outlet of the dam.

Water Quality Conditions. During the summer, thermal stratification results in anoxic conditions occurring in the hypolimnion. As a result, manganese and hydrogen sulfide accumulate. These conditions adversely affect the SYRWCD domestic water supplies for users who withdraw water from the bottom outlet of the dam.

Mitigation/Enhancement Measures. In 1981, a diffused air injection reaeration system was installed near the outlet works of Bradbury Dam. This system was designed to treat only the lower basin of the reservoir. It consists of a compressor that pumps air to four diffusers suspended about 30 to 40 feet off the bottom.

Before the aeration system was installed, water quality usually deteriorated to extremely poor levels by early August. With the aeration system in place and beginning in April, the lower basin of Lake Cachuma was sufficiently aerated to extend the period of acceptable water quality about a month to a month and a half. This extension was significant to the SYRWCD water suppliers.

In 1985, the SYRWCD added a flexible extension to the bottom outlet withdraw that allowed water to be withdrawn from the well-oxygenated waters of the epilimnion. The new outlet was operated with the aeration system in 1985, but the district operated it without the aeration system during the summers of 1986 and 1987. So far, the SYRWCD has been very satisfied with using the flexible outlet alone.

## EUTROPHICATION

**Guntersville Reservoir and Dam**
Operating Agency: Tennessee Valley Authority

Location. Guntersville Dam is located on the Tennessee River at river mile 349.0 near the city of Guntersville, Alabama. Guntersville Reservoir is located in Jackson and Marshall Counties, Alabama, and Marion County, Tennessee.

Principal Features. The reservoir is 401,000 feet long. At the normal maximum pool level, the reservoir has an average volume of 1.02 million acre•feet, a maximum depth of 60 feet, and a surface area of 67,900 acres. The dam was completed in 1939.

Uses. Guntersville Reservoir is the second largest of the multipurpose reservoirs operated by the TVA for navigation, flood control, and power production. Recreation, water supply, and assimilative capacity are significant secondary uses. Four turbine generators with a total rated capacity of 102 MW are used for power production. Drawdowns are used for flood control, aquatic weed control, and vector (disease carrier) control. Eight major public and industrial users withdraw water directly from the reservoir, while there are 30 major municipal and domestic waste dischargers and 16 industrial dischargers to the reservoir. The Alabama Department of Environmental Management and the Tennessee Department of Health and Environment have identified the following as appropriate uses of the waters of the reservoir: domestic and industrial water supply, recreation, fish and aquatic life, navigation, irrigation, and livestock watering. The Guntersville Lock System is an integral part of the 650-mile water transportation channel of the Tennessee River system.

Water Quality Conditions. Guntersville Reservoir is thermally stratified in the deeper, downstream portion during the summer. The stratification results in hypolimnetic DO depression. The upstream third of the reservoir is well-mixed, while the midsection is a transition section. More than 80 percent of the nutrient budget to the reservoir is contributed by the Tennessee River.

The morphometric, hydraulic, and nutrient characteristics of Guntersville Reservoir provide ideal conditions for macrophyte and algal growth. It has been classified as highly eutrophic by several commonly used indices. Several biological and water quality parameters indicate that Guntersville Reservoir's trophic state is increasing in a eutrophic direction. Aquatic macrophyte growth, heterotrophic growth, total organic carbon, and BOD are increasing. More than 25 percent of the reservoir acreage is infested with macrophytes. Hydrilla continues to spread, with a 30 percent increase in the past three years.

Many areas of the reservoir are of limited use due to macrophyte growth. It also greatly diminishes aesthetic appeal for swimming and boating. Algal-induced taste and odor complaints from public water supply customers are common, and water treatment plants must continuously adjust chemical concentrations to provide acceptable drinking water.

From 1974 to 1983, significant downward trends in fish biomass and numbers occurred for one or more size classes of eight of the eleven dominant fish species. However, in 1985 biomass estimates were over 2.5 times greater than in 1983 and were the greater than any other time in the period of 1974 to 1983. The condition of several important game fish species in the reservoir was better than the average for all mainstem reservoirs.

Approximately 7 million recreational visits are made to Guntersville Reservoir annually. Continued water quality degradation will result in significantly fewer visits and hence revenue reductions to the local economy. Aquatic macrophytes, excessive algal growth, and to some extent declining fisheries are the most obvious problem as perceived by the public. A recent survey indicated that respondents felt the reservoir would be unusable by the year 2000 if water degradation continues at its present rate. Conversely, a 13 percent rise in visits is expected if water quality conditions remain stable.

Mitigation/Enhancement Measures. Several efforts to improve/ mitigate conditions in Guntersville Reservoir are currently being undertaken. Herbicide treatment has been used for aquatic macrophyte control, and recently grass carp were introduced. The cost-effectiveness and weed control capabilities of the herbicide and grass carp are being evaluated. The possibility of clearing boat lanes of macrophyte vegetation to allow fishermen to reach embayment areas is also being evaluated.

Sediment and nutrient controls are planned for selected subwatersheds. When these controls are implemented, in-reservoir techniques, such as sediment removal/covering and aeration, will be implemented. When used in combination with reduced pollutant loads, water quality improvements will be visible immediately. Water quality, land, and fisheries management plans have been prepared for the reservoir.

**Boone Reservoir and Dam**
Operating Agency: Tennessee Valley Authority

Location. Boone Reservoir is one of six TVA impoundments in the Holston River Basin in northeast Tennessee. Boone Dam is located on the South Fork Holston River at mile 18.6, approximately 1.4 miles below its confluence with the Watauga River.

Principal Features. Boone Reservoir was completed in 1952, is 91,900 feet long, has a maximum depth of 122 feet, and has a mean depth of 44 feet. It stores 189,100 acre•feet of water at the normal maximum pool level, and has a surface area of 4,310 acres. It has an uncontrolled drainage area of 428,000 acres, a total drainage area of 1,180,000 acres, and a 122-mile shoreline.

Uses. The primary purposes for the construction of Boone Dam and Reservoir were flood control, regulation of flows for downstream navigation, and to the extent consistent with the first two purposes, hydroelectric power generation. Flood control rules require that definite amounts of storage space be reserved from January to May. When flood control and power generation constraints permit, the reservoir pool elevation is controlled to accommodate other uses, including recreation and fishing. During the fish spawning season, the reservoir water level is held as stable as possible for a two-week period.

Water Quality Conditions. Boone Reservoir was studied and modeled by the TVA in the development of a water quality management plan. The Boone Management Plan identified use impairments due to bacterial contamination, sludge deposition, and toxicity in portions of the reservoir and its tributaries. In addition, metalimnetic oxygen depletion, eutrophication, and litter were identified as serious concerns. Boone Reservoir is the most eutrophic tributary reservoir in the TVA system. Nutrient loadings of 232 $g/m^2/yr$ Nitrogen (as **N**) and 10.7 $g/m^2/yr$ Phosphorus (as **P**) produce chlorophyll at levels ranging from 12 to 16 $mg/m^3$. Secchi depths (a measure of clarity) of 5 feet are common during the summer. A pronounced metalimnetic oxygen reduction is believed to result primarily from algal decomposition and/or respiration. These problems are the result of both point and nonpoint sources of pollution.

Mitigation/Enhancement Measures. Point sources are being dealt with by state regulatory programs. Their efforts have resulted in construction of two expanded municipal waste treatment facilities at Johnson City, Tennessee. Facilities are under construction at Bluff City, Tennessee, and Bristol, Tennessee/Virginia. In addition, Bristol is separating their combined sewers to reduce the incidence of collection system failure and hydraulic overload of the treatment plant.

Nonpoint sources of pollution to Boone Reservoir include runoff from livestock operations, cropland, urban areas, landfill and dump sites, mining areas, and construction activities. In addition, combined sewer overflows, failing septic tanks, and roadbank and streambank erosion also contribute. Nonpoint sources will be addressed by a variety of nonregulatory approaches, including waste management demonstrations, public education, and cooperative projects involving the State, EPA, TDHE, USDA, and the public.

The TVA is carrying out several tasks in 1987-88 to address the following: animal waste management, houseboat waste management, productivity management, and biological evaluation of stream segments impacted by toxics. During 1988, the installation of four animal waste management systems is planned, as well as educating the public on the need for animal waste management systems. Presently 19 of the worst case operations have applied for the TVA cost share program. Four of these have been selected for initial installation, and the effectiveness of the systems for eliminating bacteria from the streams will be monitored. In 1987, pre-installation monitoring was initiated and will continue into the beginning of 1988 to provide a preliminary data base on bacterial contamination. Once the systems are completed, a monitoring program will determine the effectiveness of the measures.

The TVA is evaluating methods of dealing with houseboat wastes and, in cooperation with marina operators, will install one or more treatment facilities. Public education activities will be used to encourage use of these facilities.

**Eau Galle Lake and Dam**
Operating Agency: Corps of Engineers

Location. Eau Galle Dam is located on the Eau Galle River immediately upstream from Spring Valley in west central Wisconsin, approximately 50 miles east of St. Paul, Minnesota.

Principal Features. The lake is 3,300 feet long, has a volume of 1,500 acre•feet, a maximum depth of 30 feet, a surface area of 150 acres, and a shoreline length of 25 miles. The watershed has an area of 41,000 acres, with land use primarily dedicated to dairy operations and associated agriculture, pastureland, and woodlots.

The dam is a rolled-earth and rock-filled structure and was completed in 1968. The outlet structure provides for both surface and bottom releases. The reservoir was filled in 1969.

Uses. Eau Galle Dam and Lake were authorized by the Flood Control Act of 1958 to provide flood control for the village of Spring Valley, Wisconsin, and associated downstream areas. Additional uses include recreation and fish and wildlife habitat.

Water Quality Conditions. Eau Galle Lake is thermally stratified with seasonal anoxic conditions occurring in the hypolimnion. It is considered to be eutrophic and exhibits excessive algal and macrophyte growth. Seasonal high flow events dominate the external loading of nutrients. The growth of algae and macrophytes, coupled with episodic tributary loading, contribute to reduced transparency and the establishment of nutrient-rich sediments.

The release of cool hypolimnetic water through the low-level gate outflow increases the heat content of the lake and reduces the thermal stability of the lake. The reduced thermal stability and wind-induced mixing result in exchange between phosphorus-rich hypolimnetic waters and the epilimnetic waters, suggesting that internal phosphorus loadings may be significant in the lake.

Mitigation/Enhancement Measures. In 1986, hypolimnetic application of aluminum sulfate was conducted to control internal phosphorus recycling from anoxic sediments. Following application, phosphorus concentrations in bottom waters, internal phosphorus loading rate, and the abundance of algae were reduced relative to previous years. Prior to treatment, summer internal phosphorus loadings (as **P**) averaged 15.6 mg/sq m/day. Following application, internal phosphorus loadings were reduced to 6.5 mg/sq m/day. Algal biomass remained relatively high after treatment. The high levels are related to the proliferation of an algal species, Ceratium sp., that has the ability to migrate vertically in the water column. The algae may have obtained additional sources of phosphorus from nutrient-rich river waters, which enter the lake in a density current at the depth of the thermocline. The effectiveness and longevity of the treatment, as well as mechanisms governing algal abundance, will be more completely assessed during ongoing studies.

## FLOW REGULATION/REAERATION DENIAL

### Norris Reservoir and Dam

Operating Agency: Tennessee Valley Authority

Location. Norris Dam is located on the Clinch River at river mile 79.8 in northeast Tennessee.

Principal Features. The reservoir is 385,000 feet long. At normal maximum pool level, it has an average volume of 2.04 million acre•feet, a maximum depth of 200 feet, and a surface area of 34,200 acres.

Uses. Norris Reservoir is a multi-purpose reservoir, primarily used for flood control, navigation, and hydropower production. Secondary uses include recreation, fish and aquatic life, water supply, and assimilative capacity. The rated capacity for power production is 101 MW, produced by two Francis turbines. Hydropower operations provide cold water conditions suitable for "trout waters" and have been so classified by the State of Tennessee. Cold water releases also benefit the steam electric power generation plant located downstream on Melton Hill Reservoir. The tailwater extends 15 miles to the headwaters of Melton Hill Reservoir, and is used for boat, bank, and wade fishing. Boat fishing occurs when turbines are operating, while bank and wade fishing are limited to primarily when the turbines are not operating.

Hydropower production causes a fluctuation in the tailwater level of about 6 feet, with the river width changing from approximately 432 feet to 310 feet. Until 1984, minimum streamflow downstream from the dam consisted of leakage from the dam, and there were no hydropower releases for an average of three weeks.

Water Quality Conditions. A study of the tailwaters conducted from 1971 to 1977 identified low DO and inadequate minimum flow as the primary factors limiting further development of the trout fishery. The benthic fauna were dominated by tolerant organisms, while the fish condition factor, a ratio of the weight of a fish to its length, decreased an average of 11 percent each year during periods when DO levels decreased. Until 1981, DO concentrations in the hydropower releases remained less than 6 mg/l for an average of approximately one-third of the year, and remained less than 3 mg/l for 55 days during periods of hydropower releases. When DO concentrations were at minimum levels and both turbines were operating, releases would flow about 13 miles before natural aeration resulted in an increase to about 5 mg/l.

Mitigation/Enhancement Measures. In 1981, a hub baffle aeration system was installed on the two turbines. It resulted in increases of minimum DO concentrations of 2 to 3 mg/l in released waters. The aeration system was operated when DO in the hydropower scrollcase decreased in concentration to less than 4 mg/l, with a resulting minimum DO of 3 mg/l.

Greater minimum flows have been maintained since 1984 by the construction of a flow regulation weir approximately two miles downstream from the dam. Water stored behind the weir, supplied by pulsed flow from the hydropower units, has since provided a minimum downstream flow of approximately 200 $ft^3$/sec. Approximate one-half hour discharges from one turbine is required to fill the pool behind the weir, which can then supply flow downstream for 12 hours.

In an effort to speed recovery of tailwaters, desirable benthic invertebrates were transplanted to these waters. There has also been an increase in the stocking of fingerling and catchable rainbow and brown trout. There is an apparent trend toward improving trout condition following aeration, although there are no statistically significant differences between the pre-aeration and post-aeration years. Although the tailwater benthic fauna continue to be dominated by tolerant species, less tolerant organisms, which are also desirable food for trout, are occurring more frequently. The 1987 benthic fauna samples showed a large increase in mayfly abundance, which may signal the beginning of a more rapid recovery. Caddisflies, crayfish, snails, and mayflies are also beginning to influence the benthic community structure. The delayed, and as yet incomplete, recovery of the tailwater benthic fauna community may be because (1) the DO concentrations are still too low to allow survival of some sensitive species, (2) there is a shortage of colonizers of sensitive forms, or (3) because full recovery simply takes longer than expected.

Together, all mitigative efforts have dramatically improved the fishery of Norris tailwater. During 1980-83, when DO improvements were made and public awareness of the fishery at Norris increased, a 17 percent increase in fishing effort occurred. Following the establishment of minimum flow conditions, angling pressure increased 79 percent from the 1970s and was also significantly greater than 1980-83. Total annual trout harvest increased 77 percent in the 1980s compared to the 1970s, while the average annual catch rates improved from 0.34 fish/hr in 1973-74 to 0.42 fish/hr for 1980-85. These increases are attributable to a number of factors, including public interest and awareness of efforts to improve the fisheries; provision of more stable, aesthetically pleasing and more "fishable" waters by the maintenance of a minimum flow; and additional access created by the flow regulation weir.

Presently, the recovery of benthic fauna may not yet be complete, and growth of individual trout has only been minimally affected, but the fishery as a whole has dramatically improved. The fishery will continue to be monitored to evaluate sufficient DO and flow conditions.

**Mark Twain Lake and Clarence Cannon Dam**
Operating Agency: Corps of Engineers

Location. Clarence Cannon Dam is located on the Salt River at river mile 63 in northeastern Missouri.

Principal Features. The reservoir is 132,000 feet long, and has an active storage volume of 457,000 acre•feet, a surface area of 18,600 acres, a shoreline of 285 miles, and a drainage basin of 1,470,000 acres. Approximately 400 feet upstream from the main dam is a temperature control weir that allows the withdrawal of epilimnetic water that is warmer and higher in DO than the release of the hypolimnetic waters.

Uses. The uses of the reservoir consist of flood control, hydropower generation, water supply, fish and wildlife conservation, recreation, and incidental navigation for the Missouri River during low flow periods. The power installation consists of two turbines, one 31,000 kW reversible and one 27,000 kW conventional.

Water Quality Conditions. When the reservoir is not stratified, or when the thermocline-oxycline are below the temperature control weir, no water quality problems are experienced in the releases during hydropower generation. However, if the thermocline-oxycline is above the level of the temperature control weir, as has been observed from July through mid-September, poor quality water is pulled over the weir and released during power generation. This occurs until sufficient force flexes the thermocline downward, resulting in mostly epilimnetic water being pulled over the weir.

Mitigation/Enhancement Measures. The problem of poor water quality releases at power generation start-up is currently being studied. One alternative being considered is a hydraulic or pneumatic destratification system for the mini-lake area between periods of generation, and also when minimum releases are being made and the tainter gates cannot be used.

**Fort Patrick Henry Reservoir and Dam**
Operating Agency: Tennessee Valley Authority

Location. Fort Patrick Henry Dam is located on the South Fork Holston River at river mile 8.2, near Kingsport in northeast Tennessee.

Principal Features. The reservoir is 54,900 feet in length and has a maximum depth of 80 feet. At normal maximum pool the reservoir has an area of 872 acres, a volume of 26,900 acre•feet, and a shoreline of 37 miles. The drainage area at the dam is 1,220,000 acres. The South Fork Holston is a highly developed watershed with three major reservoirs located upstream from the dam.

Uses. The reservoir is primarily used for hydropower production. The rated capacity for power production is 36 MW, produced by two Kaplan turbines. Significant secondary uses of the reservoir include recreation, fish and aquatic life, water supply, and assimilative capacity. A trout fishery was created four miles downstream from the dam, at which point a thermal load is added to the river by a large chemical plant that predates the dam.

Water Quality Conditions. Hydropower releases from Fort Patrick Henry Dam have low DO concentrations. Dissolved oxygen was less than 6 mg/l for about 102 days each year, less than 5 mg/l for 62 days and less than 4 mg/l for 25 days. Periodically, the DO has reached 3 mg/l. The releases naturally aerate from 3 mg/l to about 4 mg/l within 5 miles and to about 5 mg/l within 10 miles.

The reach of South Fork Holston River below Fort Patrick Henry Dam and the upper reach of the Holston River receive waste from 13 industries and the city of Kingsport. The quantity of waste discharged exceeds the natural capacity of the river, and several dischargers provide treatment beyond best practicable. The reduced DO conditions of the dam contribute to the low assimilative capacity of these reaches. Lack of sufficient streamflow was one limiting factor for future growth and development in the Kingsport area.

The principal discharger to the South Fork Holston River, the Tennessee Eastman Company, contracted with the TVA to provide a minimum daily release of 750 $ft^3$/sec for supply purposes. This flow is therefore available for assimilative capacity purposes.

Although DO concentrations are seasonally low in the Fort Patrick Henry Reservoir, the primary focus of low DO concern has been in the Holsten River below Kingsport, downstream from the dam. At this point, the DO has been observed to be 3 mg/l during concurrent low flows on the North and South Forks of the Holston.

Mitigation/Enhancement Measures. From December 1983 to May 1985, the TVA participated in a joint study with EPA, the State of Tennessee, and major industrial dischargers from Kingsport to assess current water quality conditions and evaluate the cost-effectiveness of various DO improvement strategies. Modeling results of the river indicated that flow in the North and South Forks had the greatest effect on DO below Kingsport, and the natural aeration, photosynthesis, and respiration had the next greatest impacts. Several DO improvement strategies were simulated and their cost-effectiveness determined. It was found that using supplemental evening flow pulses could produce DO concentrations beyond that achievable with more traditional treatments, even treatment facilities upgraded to zero waste discharges. The evening flow pulses use hydro power generation of varying durations, each strategically timed to arrive at the DO sag to relieve low DO caused by plant respiration and wasteloads during the early morning hours. Aeration of the releases, instream aeration, and combinations of the three strategies were also found to be effective strategies.

A two-year pulsing demonstration was to begin in June 1986. However, at that time Fort Patrick Henry Dam would be required to provide additional flow, on a regular basis, to meet new permit requirements for sustained flow past John Sevier Fossil-Fired Power Plant. It was therefore required to increase minimum pulsing from six one-hour pulses per day to as many as 12 pulses per day, depending on the North Fork flow and the number of units operating at the power plant. This indicated that the DO improvement due to the flow requirement would exceed the improvement expected (1 mg/l) in the reservoir releases demonstration.

With implementation of the power plant permit, significant improvements have been achieved in DO concentrations downstream from Kingsport. Additional field studies and modeling have confirmed this improvement. The frequency and duration of outages of one or more units of the power plant will be evaluated to determine if any incremental pulsing plan could be performed, through the Reservoir Release Program, to provide any additional treatment.

## SEDIMENT MOVEMENT

### Lake Red Rock and Dam

Operating Agency: Corps of Engineers

Location. Lake Red Rock is located on the Des Moines River in south-central Iowa approximately 60 miles downstream of Des Moines, Iowa.

Principal Features. Lake Red Rock is approximately 42,200 feet long, with a storage capacity of 90,000 acre•feet, a surface area of 6,300 acres, and a drainage area of 4,160,000 acres. It has a 7-day mean residence time. The lake was impounded in 1969. Agriculture is the predominate land use in the watershed, however, significant point-source loadings to the Des Moines River occur upstream near the city of Des Moines.

Uses. Lake Red Rock is a Corps of Engineers flood control reservoir. It also provides recreation.

Water Quality Conditions. The Des Moines River, in general, is highly turbid, nutrient rich, and high in dissolved and suspended solids. The high suspended solids load contributed to the lake, coupled with reductions in velocity in the broad headwater area, have resulted in the deposition of large quantities of sediment and the formation of an extensive submerged delta. Sediment accumulation varies longitudinally and laterally within the lake, with the greatest amounts occurring in the headwater area and the submerged river delta. Data collected from 1968 to 1976 revealed that the submerged delta extended approximately 3 miles into the lake from the inflow point and covered about 2,200 acres. Depths of deposition in the old river channel ranged from 4 feet at the dam to 20 feet at the lake headwater. The distribution of sediments also has impaired the use of the lake for recreational boating.

Mitigation/Enhancement Measures. In 1979, the permanent pool level was raised to elevation 728 to compensate for conservation storage lost to sediment accumulation. As of 1985, more than 39,000 acre•feet had accumulated below elevation 725, occupying about 45 percent of the storage originally reserved for the 100-year project life. An additional 33,000 acre•feet had been deposited between elevation 725 and elevation 780, the top of the flood control pool, resulting in a loss of about 4 percent of the total flood control storage. The current estimate for the sedimentation rate is approximately 3,500 acre•feet per year, about four times the original estimate.

The Rock Island District of the Corps of Engineers is currently studying a permanent increase in the conservation pool level to elevation 742 to provide 400,000 acre•feet of combined sediment/conservation storage. This proposal would decrease flood control storage by 20 percent. However, it would not prohibit controlling the project design flood. Implementation of this proposal is contingent upon completion of environmental analyses, public coordination, and approval of a revised water control plan.

## THERMAL CHANGES

### Flaming Gorge Reservoir and Dam

Operating Agency: Bureau of Reclamation

Location. Flaming Gorge Dam is located on the Green River in northeastern Utah, about 32 river miles downstream of the Utah-Wyoming border.

Principal Features. The reservoir is 475,000 feet long, with a maximum depth of 440 feet, an active capacity of 3,516,000 acre•feet, a surface area of 42,000 acres, and a 375-mile long shoreline. It drains an area of approximately 11,300,000 acres. The dam was completed in 1962.

Uses. Flaming Gorge Reservoir is a major unit of the Bureau of Reclamation's Colorado River Storage Project. It is operated primarily for power production, although it also serves the purpose of storing irrigation water. The power plant is located at the downstream toe of the dam and it houses three 36-MW generators driven by three Francis-type turbines. Reservoir releases are made almost exclusively through the three penstocks, whose intakes are located halfway up the dam. Hourly releases are determined by the power system loads, and during the summer months by maximum and minimum operating criteria for downstream recreational uses.

Water Quality Conditions. Flaming Gorge is a reservoir, with direct thermal stratification in the summer, an ice cover over most of the surface in the winter, and periods of complete mixing in the spring and fall (dimictic). However, as the reservoir filled in the late 1960s and early 1970s, a chemocline (water quality gradient) developed in the area immediately behind the dam. This chemocline was generally located below the turbine intakes at a depth of about 200 feet, while the thermocline was usually at a depth of 30 to 35 feet. The zone below the chemocline did not mix during spring and fall overturns, and the water was cold, anoxic, and poor in quality. After the selective withdrawal modifications were installed in 1978, the chemocline gradually weakened each year and finally disappeared during the spring overturn of 1982. It has not been observed since.

Water quality on the lower, canyon section of the reservoir is quite good and could be classified as being relatively oligotrophic (not enriched). A lake trout fishery had been established. In the more upstream section of the reservoir toward the tributary inflow areas, the trophic status becomes mesotrophic and finally eutrophic in the summer months in both the Black's Fork and Green River arms. Summer algal blooms are common in these warm water reaches.

After closure of Flaming Gorge Dam, the downstream aquatic environment of the Green River changed radically. Temperatures before dam closure ranged from 32°F to about 67°F. High runoff flows with heavy sediment loads occurred in late May and June. After dam closure, temperature fluctuations were reduced to a range of 39°F in March to about 50°F in November. Flows were stabilized to a power demand cycle. Sediment loads were reduced, as reflected in a drop in turbidity values, from 5,000 Jackson Turbidity Units to around 60 Jackson Turbidity Units.

The biota also changed. Indigenous fish species were replaced by rainbow trout in the 26 miles below the dam. This sport fishery quickly became a valuable recreational resource for the State of Utah. However, as the reservoir filled and stratified, the penstocks began to draw water from deeper and colder strata, reducing summer water temperatures in the tailwater area below the range necessary to maintain a self-sustaining trout fishery. By the mid-1970s, trout production in this area declined markedly.

Mitigation/Enhancement Measures. The Bureau of Reclamation, with the cooperation of the Utah Division of Wildlife Resources and the U.S. Fish and Wildlife Service, investigated various methods of controlling reservoir discharges in order to raise downstream temperatures to allow the growth and production of the trout fishery. As a result, shutter-type selective withdrawal structures were retrofitted to the three penstock intakes. The structures are square towers, each about 200 feet high, with a series of four shutters along the length of one side. They effectively extended the penstock intakes vertically upward into higher and warmer reservoir strata so that warmer water could be released downstream. The shutters are raised and lowered by hoists on the dam to selectively withdraw water of a given temperature. Modification of the penstock intakes was completed in 1978.

The selective withdrawal modification was successful in meeting the fishery water temperature criteria downstream. Fish production and condition improved. A large increase in numbers of fish food organisms in the tailwaters was also noted. Other benefits included fewer cases of hypothermia among river runners and an upstream movement of warmer water fish communities.

## NEUTRAL OR POSITIVE EFFECTS

### McCloud Reservoir and Dam

Operating Agency: Pacific Gas and Electric Company

Location. The McCloud Dam is located on the McCloud River in northern California.

Principal Features. The McCloud Reservoir has a gross capacity of 35,200 acre•feet, and a surface area of 520 acres. The drainage area covers approximately 269,000 acres and is primarily used for timber production and recreation. The dam was completed in 1965.

Uses. The McCloud Dam's primary use is to supply water to the James B. Black hydroelectric powerhouse. Up to 2,000 $ft^3/sec$ is diverted through approximately 11 miles of conduit and an intervening reservoir to the powerhouse, producing 172 MW at normal operating capacity.

Water Quality Conditions. Mud Creek, a tributary to the McCloud River near the upper end of the reservoir, carries a significant sediment load originating from the Konwakiton Glacier. Before the dam was built in 1965, elevated turbidity levels resulting from this glacial runoff occurred from midsummer to late fall or winter, depending on weather conditions.

A water quality study was performed by Pacific Gas and Electric Company due to concerns of resource management agencies regarding the effect of dam releases on levels of turbidity and temperature downstream of the reservoir. The water quality data indicate that the reservoir appears to act as a settling basin for a large portion of the material that drains to it. Turbidity of release water is generally much reduced from the levels that would have occurred if the dam had not been constructed. Although high sediment inputs from Mud Creek cause turbidity levels and total suspended solids to increase throughout the reservoir, the majority of the material that flows into the reservoir remains near the bottom.

The study also concluded that the temperature of the river immediately downstream of the McCloud Dam showed little change from that of the river upstream of the dam. The thermal structure of the reservoir, even during seasonal changes in reservoir elevation and inflow temperatures, is such that little negative effect on temperatures downstream can be expected as long as mid to lower elevation intakes are used as sources of water for downstream releases. Reservoir data also indicate that DO concentrations will remain above standards necessary for the maintenance of aquatic life. This applies regardless of the intake elevation used for downstream release.

Mitigation/Enhancement Measures. No mitigation/enhancement measures are necessary.

## SUMMARY

The fifteen case studies illustrate several water quality effects and some of the implemented and planned mitigation measures, though they are not intended to be statistically representative.

J. Percy Priest Reservoir, Old Hickory Lake, Richard B. Russell Lake, Upper Bear Creek Reservoir, Casitas Lake, and Lake Cachuma were presented as case studies of low hypolimnetic DO and/or increased concentrations of iron and manganese in the hypolimnion and tailwaters. (Old Hickory Lake does not have elevated concentrations of iron and manganese.) These effects are greatly facilitated in each case by a seasonal stratification of the impoundment. Aeration of the impoundment or tailwaters and selective withdrawal were reported as successful mitigative efforts.

Guntersville Reservoir, Boone Reservoir, and Eau Galle Lake were presented as examples of eutrophication, with phytoplankton and macrophytes causing problems. Herbicide treatments, introduction of grass carp, and hypolimnetic application of aluminum sulfate to control internal phosphorus recycling are some of the mitigation measures applied. Watershed management - including best management practices for nonpoint source and point source controls - is becoming increasingly important for reducing eutrophication.

Norris Reservoir, Mark Twain Lake, and Fort Patrick Henry Reservoir are given as case studies of flow regulation and/or reaeration denial. In these cases, management of low flows is an important issue. Flow regulation weirs and operational changes are among the mitigative measures employed.

Lake Red Rock and Flaming Gorge Reservoir were provided as examples of a sediment accumulation problem and a cold tailwater problem, respectively. The former has primarily been mitigated by altering the operational philosophy, while the cold discharges have been reduced by selective withdrawal.

Finally, McCloud Reservoir was included to demonstrate that not only do some impoundments not have any water quality problems, but they may actually improve water quality. In this case, the reservoir tends to reduce downstream turbidities caused by high sediment loads generated by a glacier.

All mitigative measures employed in the case studies were reported to be successful to some extent. In some cases, several seasons were required to completely see their effect, and in other cases, more than one measure was needed to rectify poor water quality conditions. In all cases where improvements in water quality conditions have occurred, there have been significant measurable benefits to either the public, in terms of improved fishing conditions and other recreational opportunities, or to dischargers, in terms of increased assimilative capacity.

# V. MITIGATION MEASURES

This chapter identifies major mitigation measures that can be used to address the adverse water quality effects associated with certain impoundments. Mitigation is also discussed in specific situations associated with the case studies presented in Chapter IV. Because each reservoir system is unique, the applicability of specific mitigation measures must be evaluated on a case-by-case basis. This evaluation must consider the effects that need to be corrected, the present uses of the reservoir system, as well as the benefit-cost relationship of the mitigation measures. Due to the complexity of the reservoir-tailwater system, mitigation measures have to be carefully evaluated before implementation. Implementation of more than one measure may be necessary to improve or maintain the water quality in a reservoir system. The application of one measure may correct one adverse effect, but create or intensify another water quality effect. For example, reaeration of releases to increase DO may cause a problem with nitrogen supersaturation (TVA, 1978). While mitigation measures are intended to minimize or prevent certain undesirable water quality effects, they themselves sometimes cause other adverse environmental effects. For example, gaining access to the impoundment to implement a mitigation measure may require cutting a road through a wetland. Another example might be a mitigation measure intended to control algae growth which also causes fish mortality.

When considering the appropriateness of specific mitigation measures, most operating agencies must insure that authorized project purposes are met. If the selected mitigation measure negatively affects or restricts authorized project purpose(s), its implementation often cannot be justified without a modification to the authority, regardless of its potential positive effect on water quality.

Mitigation measures can be divided into three broad categories: physical measures, operational measures, and structural modification. Physical measures include technologies that require specific processes or equipment to be used to correct the problem. Physical mitigation measures include the control of water quality in the reservoir, selective withdrawal of reservoir water with acceptable water quality, aeration of reservoir releases, and habitat modification. Operational measures include changes to the present operating regime of the reservoir system. Operational measures include maintaining a minimum discharge, limiting the maximum discharge flow, and altering the rule curves for reservoir operations as well as selective withdrawal. Structural modifications involve changes to the structure of the dam and/or its outlet works; examples would be the addition of ports, gates, vents, or weirs to modify the depth or manner in which water is selectively withdrawn from the reservoir.

The measures in this chapter are grouped according to whether they primarily affect the pool, affect the tailwater, or are of a more general nature. Frequently, mitigation measures will have an effect on both the pool and tailwater because of the complex interrelationships. Depending on site specific circumstances, all of the mitigation measures are candidates for retrofit as well as new construction.

## WATER QUALITY CONTROL IN THE RESERVOIR

Several mitigation measures are available which may be specifically applied to improve water quality in the impounded pool. These include measures for induced mixing, hypolimnetic aeration, and dredging.

### Induced Mixing.

Induced mixing is frequently applied to stratified impoundments to mitigate water quality concerns related to stratification such as low hypolimnetic DO, increased iron and manganese, and thermal changes. Mixing may be induced by the use of low head, high volume mechanical pumps pushing epilimnion waters into the hypolimnion or vice versa (TVA, 1978). Mixing may also be induced by air injection in the hypolimnion, which will tend to move upward with the gas bubbles. If sufficient air is introduced, the process may continue until a stratified impoundment experiences nearly uniform temperature and DO distributions (Fast, 1979).

Induced mixing may be applicable to reservoirs of any size (USEPA, 1973). However, it is not always necessary to destratify an entire reservoir; only the area near the outlet structure may require mixing. TVA is experimenting at Douglas Dam with three high-volume, low-speed axial pumps just upstream from turbine intakes; the pumps force oxygenated epilimnetic water into turbine intakes during stratified periods (TVA, 1987a).

In addition to increasing DO by the introduction of air and/or the movement of anoxic hypolimnetic waters to the surface where they can be reoxygenated, mixing can also reduce the occurrence of dissolved iron and manganese and hydrogen sulfide that are soluble under anaerobic conditions. If this occurs, the taste and odor characteristics of the impoundment waters can be improved.

Induced mixing may also result in increasing the total energy (heat) content of the water body during the summer months, since the average temperature of the mixed impoundment will more closely approximate the epilimnion temperature before mixing. If destratification is successful, the cold hypolimnetic waters may be eliminated. Destratification is generally considered beneficial for warm water fish, since there is an increase in their depth distribution, and therefore, an increase in available habitat. An increase in food supply is often observed since benthic fauna production often increases greatly during mixing (Fast, 1979). This is, in part, a result of reduction of barriers to the distribution of fish, zooplankton, benthic fauna, and other biota (Fast, 1979). However, in some cases, this effect may be undesirable because it can eliminate cold water fish species. Destratification also increases the temperature of the water released into the tailwaters. It therefore may not be appropriate where cold water fisheries are supported, but may support management of warm water fisheries that in the past have been impaired by cold water releases of the hypolimnion.

Destratification, through mixing, is notably less effective in reducing algal densities and primary production. It can upwell nutrients into the euphotic zone and thereby stimulate algal growth.

**<u>Aeration of the Hypolimnion</u>.**

Aeration of the hypolimnion can be performed with the intention of mixing, as described above, or simply to provide additional oxygen to targeted regions of an impoundment. In reservoirs where the cold water of the hypolimnion and releases are desirable, but the water quality is poor, aeration of the hypolimnion may be applicable. Aeration strips undesirable gases such as carbon dioxide, hydrogen sulfide, and ammonia (Fast, 1979), and lowers the concentration of iron, manganese, phosphorus and other conditions associated with anaerobic conditions. Small changes in temperature usually occur, but cold temperatures are maintained. Artificial aeration will not affect external loadings of nutrients, but it may affect the rates and directions of nutrient cycling once the nutrients are in the reservoir, and in cases where the internal loading of nutrients is significant, aeration may alleviate some of the symptoms of eutrophication. It can increase species diversity by increasing the suitable habitat available for cold water species such as trout, salmon, zooplankton, and benthic fauna. Like mixing, aeration is not always successful in reducing the algal standing crop.

Aeration of the hypolimnion of small water supply reservoirs has been demonstrated to be effective (TVA, 1978). However, it may not be economical for large reservoirs that are used for power production due to the large volume of hypolimnetic waters that is continually released through the turbines. Another drawback of aeration is the possibility of supersaturation of nitrogen gas occurring in the hypolimnion and in the tailwaters. Use of pure oxygen gas for aeration is one solution to this problem.

Methods that control DO within the reservoir generally result in better overall water quality than those that only increase DO levels in the releases. However, mitigative measures applied in the reservoir may not ensure a targeted concentration of DO in the tailwaters and may require supplemental aeration. Full-scale projects by the Corps of Engineers and EPA have demonstrated that one disadvantage of the method is that DO levels in the tailwater releases cannot be regulated very readily (TVA, 1978), and aeration of the tailwaters may still be necessary.

**Dredging**.

Dredging is the only mitigative measure that directly removes the accumulated products of degradation from the reservoir, thereby increasing depths and removing potentially recyclable nutrients (Peterson, 1979). Increase in water depth is especially important for reservoirs since they serve as sediment traps and therefore become shallower with time. Dredging can remove aquatic vegetation, which is especially important where unwanted species have invaded a reservoir system. It can minimize the role of the sediments in recycling nutrients and can lower the oxygen demand of the sediments by removing organic matter. In Long Lake, Michigan, dredging was successfully used to improve the fish habitat by increasing lake size and depth and decreasing the amount of organic sediment (Peterson, 1979).

The disadvantages of dredging relate to environmental concerns as well as economics. Dredging causes resuspension of bottom sediment and toxic substances, resolubilization of chemicals, and can cause oxygen depletion by resuspending settled organic matter. Resuspension of sediments may reduce primary production rates due to decreased light penetration in turbid waters, and nutrient levels may increase due to their liberation from deep anaerobic water areas during dredging. Dredging removes a large number of benthic organisms and can reduce fish production by decreasing their food supply and spawning areas. Dredging is costly and requires a disposal site.

## WATER QUALITY CONTROL OF TAILWATERS

Additional mitigative measures are directly applicable for improvements of water quality in the tailwaters. These measures include aeration of reservoir releases, selective withdrawals, and habitat improvement.

**Aeration of Reservoir Releases**.

For a reservoir to discharge water with sufficient DO concentrations to meet water quality standards, aeration of reservoir releases may be necessary. This has been successful in tailwaters that receive hypolimnetic waters. Most tailwater water quality effects are centered on dam releases and their oxygen status.

Under contract to the Corps of Engineers EWQOS program, TVA reported upon techniques for reaeration of hydropower releases (CE, 1983). Although aeration may be applied in the tailrace or immediately downstream, TVA found that most of the research and development activities of the prior decade have been directed toward turbine venting or aeration in the reservoir itself. Imbedded within the TVA report is a translation, from German, of a review by Dr. Peter Volkart that also deals with turbine venting as well as diffused air, cascade, surface, and pure oxygen aerators. Such processes could play a role in situations where dissolved oxygen is needed and turbine venting is not an option. Dr. Volkart points out that surface aerators are efficient oxygen transfer devices, which explains their common use in wastewater treatment applications.

*Turbine venting* is a process in which water is aerated as it passes through a hydroelectric turbine. Venting is used not only for oxygenation, but as a means to control cavitation and vibration. The process is one in which air is aspirated or drawn into partial vacuum regions which occur naturally or are created below the turbine in the draft tube. A vacuum is created through the installation of baffles or deflector plates near vent holes which cause a flow separation and localized low pressure areas near the vent openings. There are similarities between this process and the lift associated with an airplane wing created as air flows over the wing causing a vacuum on the underside.

The TVA team (CE, 1983) reported on turbine venting in the United States and Europe, including efforts by Duke Power, Alabama Power, Union Electric, TVA itself, and others. Various hub baffle schemes retrofitted as field modifications to existing turbines are presented and discussed. Configurations included oxygen diffusers in the turbine flow, aspiration into the draft tube below the turbine wheel, and mechanical injection by compressors. As a process, turbine venting can greatly increase dissolved oxygen, and many schemes may only be operated as needed. A disadvantage is a slight drop off in power production when venting is underway.

TVA is evaluating a number of strategies for improving reservoir releases (TVA, 1987a). At Appalachia Dam, flow reversion from the powerhouse tunnel to the stream reach below the dam is being studied. Turbine baffles or extra aspiration piping are being studied at Cherokee, Norris, and South Holston dams. At Tims Ford, an air compressor is used to inject air into dam releases. Turbine pulsing is being tried at Fort Patrick Henry and Norris Dam; this strategy alternatively increases and decreases the flows in the reach below the dams. As part of these site-specific tests and evaluations, TVA measures dissolved oxygen improvements and considers the associated costs.

**Selective Withdrawal of Reservoir Water.**

Thermal stratification of a reservoir can allow for the selective withdrawal of strata with the best water quality for tailwater conditions. For example, a water level that contains an acceptable DO concentration and temperature could be released. Since the level at which appropriate water quality conditions may occur changes, multi-level intake structures may be necessary. The success of selective withdrawal also depends on the required volume of water that has to be discharged compared to the volume of water available in each strata. Fishery problems can arise when the volume of cold water released in a reservoir runs out in mid-summer and warm water must suddenly be released. This situation precludes support of both cold water and warm water fisheries. Construction of multi-level intake structures may be too expensive for existing dams in comparison to the benefits that will be achieved. It is possible to predict the water quality and hydraulic effects that selective withdrawals may have on reservoir waters using mathematical models to determine if such expense is warranted.

Submerged weirs have been used to allow only well-oxygenated surface water to pass through power units. All submerged weirs now in use are permanent structures located upstream from the base of the dam (TVA, 1978). These structures are not well-suited for reservoirs whose pool levels fluctuate considerably. The crest of the weir must be at a relatively low depth to allow water to pass over it during all times of the year. Hypolimnetic waters can then pass over the weir when the reservoir is at normal operating levels during the summer (TVA, 1978).

**Habitat Improvement of Tailwaters.**

Tailwater management to support fisheries is a relatively new science developed over the past thirty years. The first time it was noted that warm water species of fish did not reproduce below a dam was in 1943 (Pfitzer, 1975). In the years that followed, this phenomenon was repeated each time a high dam was completed and discharged cold water into formerly warm water (Pfitzer, 1975). However, with proper management many tailwaters can support excellent fisheries.

Tailwaters otherwise suitable for fisheries, but limited by inadequate minimum flow and low concentrations of DO, might be improved by physical changes to the environment. One method of habitat improvement related to the problem of minimum flow is increasing the area of continuously wet substrate and the extent of reaches with deep water. This can be accomplished by multiple rock structures, small dams, and wing walls, which all result in formation of a series of small pools separated by reaches of fast, turbulent water. These structures can also serve to increase turbulence, and therefore DO. Unfortunately these structures would not solve the problem of low DO during periods of maximum discharge.

Another method to improve the habitat of tailwaters is flow regulation of the discharge waters. A fairly accurate habitat maintenance flow can be determined by studying shoal and riffle areas at different flow regimes. There is an ideal minimum flow that would maximize fisheries (Wiley and Mullen, 1975). Usually a compromise flow is implemented as a result of conflicting needs of other uses of the reservoir. The problem of control of releases is also discussed in the Operational Changes section.

The Fish and Wildlife Service has developed a detailed methodology to evaluate habitat (FWS, 1982). Their method is termed the "Instream Flow Methodology" and is one of the methods used in Federal Energy Regulatory Commission (FERC) licensing proceedings to evaluate the downstream impacts of hydroelectric projects on aquatic habitats. Physical changes to the tailwaters (artificial spawning areas) and operational changes are sometimes required to receive a license to generate power. The method can be applied in a variety of situations.

## OTHER MITIGATION MEASURES

Other mitigation measures of a more general nature may be applied. These measures have the potential for improving water quality in the pool and tailwaters. These measures are predominantly of a management nature and include watershed management and changes in dam operations.

### Watershed Management.

The two major sources of pollutants entering a reservoir are nonpoint sources and point sources. Since adequate treatment measures for point sources of pollution have already largely been installed, this section will focus on controlling nonpoint sources of pollution in the watershed. There are numerous and divergent sources of nonpoint source pollution, and each type of source has its own type of treatment. For example, sediment transport to a large reservoir can be dispersed by smaller upstream impoundments. Major land uses in the watershed, such as agricultural, urban development, and suburban development, contribute to nonpoint source pollution in different ways. Therefore, the controls implemented depend on the watershed land use.

Watershed management for nonpoint source pollution also requires the cooperation and interaction of citizens, local governments, and state and Federal agencies. One mechanism that has aided the implementation of nonpoint source controls has been the formation of watershed districts that serve as focal points for the identification of pollution problems and for allocating funds for improvements. For example, at White Clay Lake in Wisconsin, the creation of a Lake Protection District allowed local citizens the opportunity to assist in the development and implementation of land management plans (Peterson, 1979). It can also help increase the public awareness of the possible controls and the contribution individuals can make in reducing pollution.

Watershed management for reservoir water quality is extremely important, yet difficult to effectively institutionalize. Reservoir management agencies often have little or no administrative or regulatory responsibility or authority in the watershed. Thus, they are faced with the difficult task of dealing with the symptoms rather than the cause of poor water quality. If the water quality of reservoirs is to be adequately managed, greater emphasis must be placed on the development of cooperative management approaches on a watershed-wide basis. This will often require interagency cooperation. An example of this recent level of concern is the Chesapeake Bay Agreement, reached in 1987 by the governors of the states with watersheds draining into the Bay. The governors formally - and very publicly - agreed to establish state-wide, watershed management programs, to reduce nutrient inputs to the Bay by 40 percent over the next ten to twenty years. Improved quality of the Bay is the overriding goal. In a similar attempt, TVA is also organizing county-level activities designed to control nonpoint source inputs through watershed management.

One of the most visually evident sources of nonpoint source pollution is soil erosion, resulting in sediment loads transported to, and deposited in, reservoirs and the streams that feed them. Also transported along with the sediments are solid mineral and organic matter, and absorbed chemicals such as pesticides, herbicides, and nutrients. There are numerous methods to help control soil erosion. Examples include: limiting the extent and exposure time of bare ground; keeping bare ground covered with mulches or protective matting during construction activities; limiting construction to periods of minimal precipitation; diverting runoff around exposed areas; utilizing settling basins and silt retaining fences to reduce runoff velocity and to trap suspended sediments; sloping reservoir banks to facilitate vegetation; seeding exposed banks and revegetating banks with natural trees and shrubs for erosion and thermal protection; and in areas where this is not possible, installing rip rap (USEPA, 1977). Construction activities in the watershed can greatly impact the sediment load to the reservoir. Enforcing the implementation of the above measures during construction activities can greatly reduce erosion.

Since dissolved pollutants such as nutrients will not be removed by the above methods, different approaches must be utilized for their control. Optimum application rates of pesticides, fertilizers, and herbicides, as well as timing considerations are important, along with suitable disposal of wastes with their application (USEPA, 1977). Education of the public in the proper use of fertilizers, herbicides, and pesticides can be especially important. In areas where these impacts are critical, regulation of the time and extent of their use may be necessary.

Depending on the location of the reservoir watershed, urban or agricultural nonpoint sources may be major contributors of pollution. There are numerous programs already designed to help farmers control the loss of sediment, nutrients, and chemicals from their cropland and pasturelands. These are not only effective in controlling pollution, but also help reduce farming costs and increase farming efficiency. Examples of agricultural management practices include contour farming, conservation tillage, livestock waste management systems, and crop residue management. There are also numerous methods to control urban runoff that either reduce runoff or delay runoff, such as increasing the extent of pervious areas, and ponding and detention measures for impervious areas. Frequently, however, these options are limited because the operating agency for a dam may lack the authority and/or the necessary cooperation to implement these measures.

**Operational Changes**.

Water quality impacts may be lessened by changes in the operational procedures of a dam. However, the majority of dams are not, and cannot be, operated solely for the purpose of achieving water quality objectives. Conflict of interest can occur if water quality objectives are added to the other primary operational purposes of the reservoir, such as flood control or power generation. The losses due to changes in operation for the primary uses would have to be compared to the benefits of protecting or enhancing stream uses.

While the majority of reservoirs are not operated for the specific purpose of water quality, most Corps of Engineers reservoirs are operated to achieve water quality goals within operational constraints. Water control plans for Corps of Engineers projects are developed to meet the authorized project purposes. Deviations from these plans can be accommodated only if there is no adverse impact on the authorized purposes; otherwise, additional authority is required. Most other involved federal agencies have similar constraints. Changing operations requires justifications and authorizations.

The requirement to maintain a minimum, constant discharge would greatly benefit tailwaters where zero discharge occurs periodically. The advantages of maintaining a minimum flow is that it helps avoid rapid temperature fluctuations, reduces the impact of low DO concentrations through natural aeration in the tailrace, and increases the continuously wet surface area of the stream, therefore increasing habitats for benthic biota and fish. The drawbacks of this change in operation are that it causes a loss in the flexibility of peak-power operation and a decrease in power operation efficiency. Discharges of less than minimums required to operate turbines in power dams may have to be sluiced, leading to a complete loss of the energy potential of this water. Reservoir water levels may also be affected, adding to the complexity of river management and flood control (TVA, 1978, 1987a).

One compromise type minimum flow is a time-volume release, in which relatively large volumes of water are released in short pulses during periods of otherwise no discharge. For example, at a project where two- or three-day periods of no-flow may frequently occur from March to October, a release schedule could be adopted that would allow a brief discharge of perhaps one full load on one generator. TVA is evaluating such turbine pulsing (TVA, 1987a). Such a discharge schedule may occasionally result in a minor loss in total system power production capability. The discharge of water following this schedule would permit electrical power to be generated and at the same time provide fresh volumes of cold water in the tailwater (Pfitzer, 1975).

Limiting discharge to a certain maximum flow reduces impacts on DO during the period of low concentrations in the discharges through natural aeration in the tailwaters. This method involves a loss of flexibility in peak-power generation and may place unacceptable constraints on flood control operations (TVA, 1978).

## VI. FEDERAL AGENCIES' WATER QUALITY ASSESSMENTS OF IMPOUNDMENTS

### INTRODUCTION

This chapter presents the results of assessments by the Corps of Engineers (COE), Tennessee Valley Authority (TVA), and the Bureau of Reclamation (USBR) of water quality at their impoundments. These three agencies specifically requested that they be allowed to contribute individual assessments of the dams they manage. None of the other commenters offered similar assessments.

Water impoundments operated by these three Agencies represent a wide variety of geography, climate, and operational situations. COE dams are concentrated in the industrialized areas of the Southeast and the Ohio River Basin, coastal areas, the Pacific Northwest, and along mainstem navigable rivers. TVA dams are located in a well-developed and partially industrialized extended river basin. USBR dams are located solely in the 17 western states and Hawaii. These Agencies were invited to prepare their Agency assessments as a supplement to this Report to Congress in recognition of the importance of regional effects and site-specific characteristics on dam water quality. The original submittals by the Agencies are provided in the appendices (Appendix F, COE; Appendix G, TVA; and Appendix H, USBR). These original submittals provide the following information specific to each Agency's area of interest:

(1) Statement of policies and procedures followed by the agency in the development and management of water resources.

(2) Assessment of water quality with respect to the agency's dams.

The three Agencies adopted a questionnaire developed by Kennedy, Gunkel, and Gaugush of the U.S. Army Corps of Engineers Waterways Experiment Station (WES) at Vicksburg, Mississippi, as a uniform instrument for collecting dam-related water quality information on their respective projects. A copy of the questionnaire tailored to the USBR, with its instruction sheet, is attached as Appendix I.

Basically, the questionnaire presents field personnel with a comprehensive list of water quality attributes. They were asked to subjectively rate each attribute in the tributary, pool, and tailwater of each reservoir on the basis of the extent to which this attribute is a problem, the level of impact of the attribute on user benefits, and the reliability of the data upon which the rating is being made. A computer program, also developed at WES, compiles the data from the questionnaires into a SAS data file. Statistical analyses can then be performed on the various attributes and their ratings using the SAS software. In the short time allowed for this study, the three Agencies limited their efforts to frequency analyses of each attribute's extent and impact in the pools and tailwaters of their reservoirs.

The Agencies feel the limited analysis presented herein gives an accurate picture of the known extent of given water quality conditions across a broad range of geography, climate, and project operating criteria, along with an assessment of the perceived impacts of these conditions on user benefits. This information is presented from the point of view of field personnel who are directly responsible for daily dam operations and the delivery of promised project benefits.

The remainder of this chapter contains summaries of the results of each Agency's assessment of water quality related to its dams and recommended research needs, followed by an overview of the data presented. Material submitted by the Agencies has been incorporated directly into this chapter.

## CORPS OF ENGINEERS

### Background.

The Corps of Engineers has constructed and now operates more than 700 water resource projects having a total surface area of nearly 10,000 square miles. The geographic distribution of these projects, as depicted in Figure VI-1, reflects regional differences in water resource development requirements, water control agency responsibilities, and topographic requirements for cost-effective construction. Impoundments providing navigation benefits, which comprise approximately 26 percent of all Corps projects, are located along major inland waterways. These include the Mississippi River and its major tributaries, the Arkansas and Red Rivers draining from the west, and the Ohio and Illinois Rivers draining from the east. Other waterways of importance include the Alabama River and the Tennessee-Tombigbee Waterway in the mid-south, and the Columbia River in the northwest. Twenty-one percent of all projects are dry dams or projects which, by design, provide minimal permanent water storage during nonflood periods. These projects are most prevalent in the arid southwest, where flooding conditions are associated with intermittent periods of excessive runoff, and in the New England states.

Reservoir projects providing short- and long-term storage of water, but not navigation benefits, comprise the remaining 53 percent of all COE water resource projects. These projects can be broadly categorized based on reservoir morphometry and tributary type. Deep, storage reservoirs are formed by the impoundment of higher order streams and rivers, and are frequently located in deep, steeply-sloped river valleys. These projects tend to be deep, narrow, and highly dendritic in shape. Mainstem reservoirs are located on lower order (i.e., larger) rivers and tend to be shallower, wider, and less complex in shape.

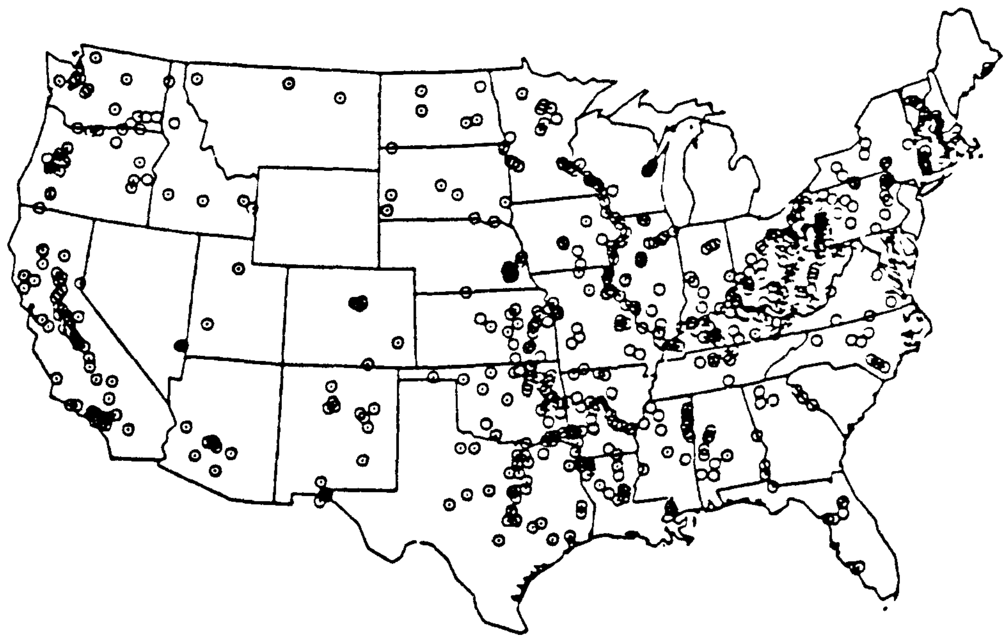


FIGURE VI-1. - Geographic distribution of Corps of Engineers water resource projects.

FIGURE VI-2. - Geographic distribution of a ten percent, stratified, random sample of Corps of Engineers projects for which questionnaires have been received.

Water control management programs provide the means for operating Corps' projects to meet their authorized purposes. Most of the Corps' projects are authorized for multiple purposes (e.g., flood control, navigation, and recreation), and over 60 Corps of Engineer projects include water quality as an authorized project purpose. Flow augmentation for industrial and municipal pollution abatement, acid mine drainage abatement, and other purposes which relate to water quality, are often included in flood control and navigation projects. Water quality management objectives have been developed for each project and incorporated into Corps water control programs wherever possible.

**COE Water Quality Assessment.**

For the purposes of this report, information was obtained through the use of a questionnaire designed to solicit information concerning project design, operation, and water quality status. The questionnaires were completed by COE personnel familiar with each project and its water quality characteristics. With regard to water quality status, subjective responses to questions concerning water quality were requested. In general, these responses indicated the presence or absence of water quality problems. In situations where problems were indicated, graded responses allowed assessment of the severity of the problem and the quality of the information upon which the assessment was based. To date, questionnaires for approximately 470 of 700 projects have been completed and compiled.

Since questionnaires for all projects have not yet been completed, a sample of questionnaires was randomly drawn and analyzed by the COE for the purpose of this report. The sample size was set at 10 percent (46 projects), and samples were drawn from strata based on project type (reservoir, lock and dam, and dry dam) and COE District. The geographic locations of sampled projects are presented in Figure VI-2 for comparison with the distribution of all projects (Figure VI-1). Results presented below are based on these analyses.

Figures VI-3 and VI-4 present the water quality status of tailwaters and pools associated with the sampled projects, respectively. A shortcoming of the data upon which these figures are based is the fact that reliable information concerning water quality status is lacking for approximately 40 to 50 percent of the projects. Thus, a degree of uncertainty and/or bias exists for data discussed here, and extrapolations of data compiled for the sampled COE projects to all COE projects are not possible. The data do, however, provide a general assessment of the types of water quality concerns associated with COE water resource projects and some indication of their relation to other project attributes.

As depicted in Figure VI-3, approximately 60 to 65 percent of those sampled projects for which evaluations of the water quality status of tailwaters were available were considered not to exhibit problematic conditions. For those projects indicated as exhibiting problematic conditions, several categories of water quality concerns are apparent.

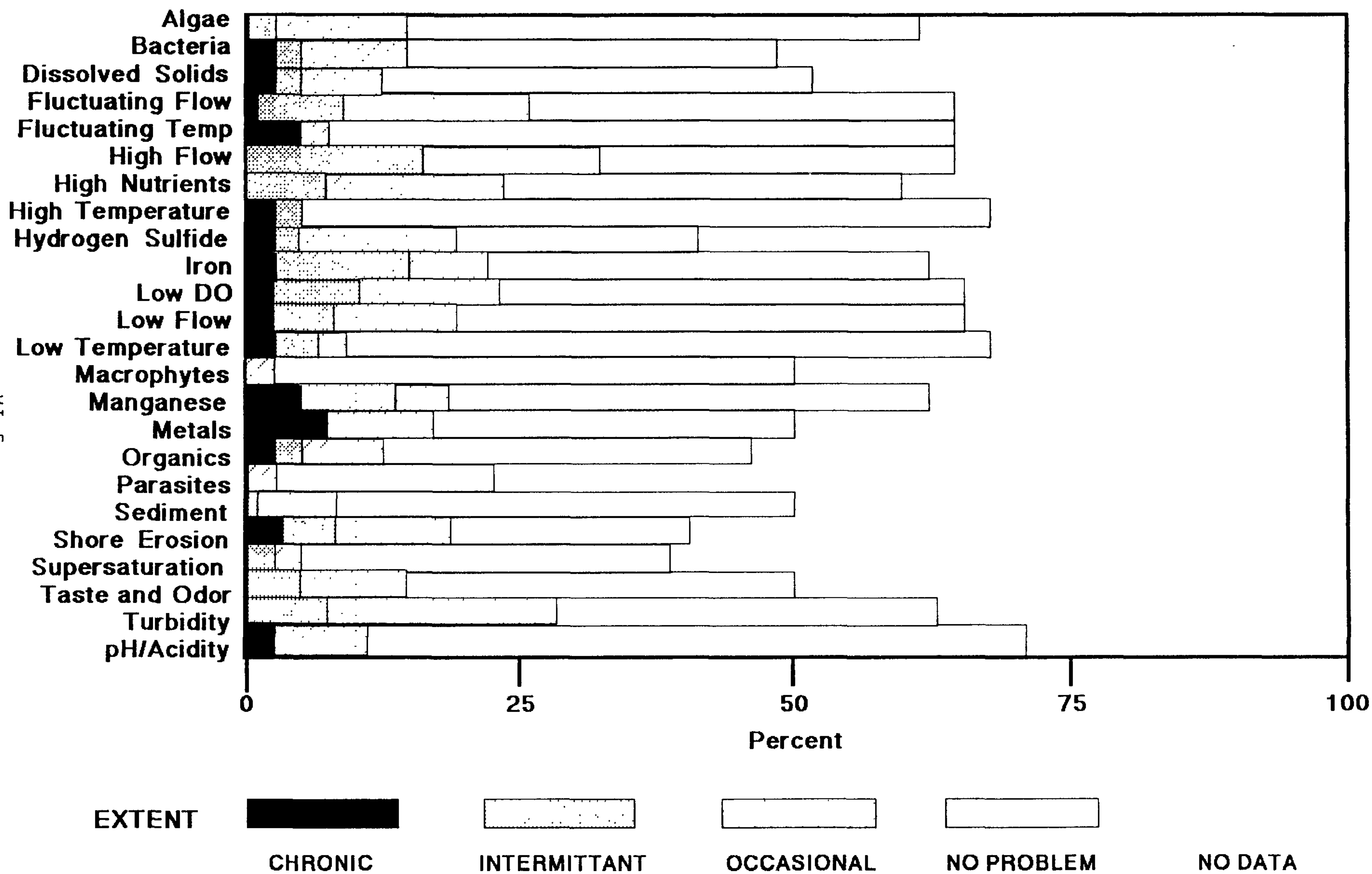



Figure VI-3 Frequency of Occurrence of Water Quality Conditions in COE Tailwaters (N = 46).

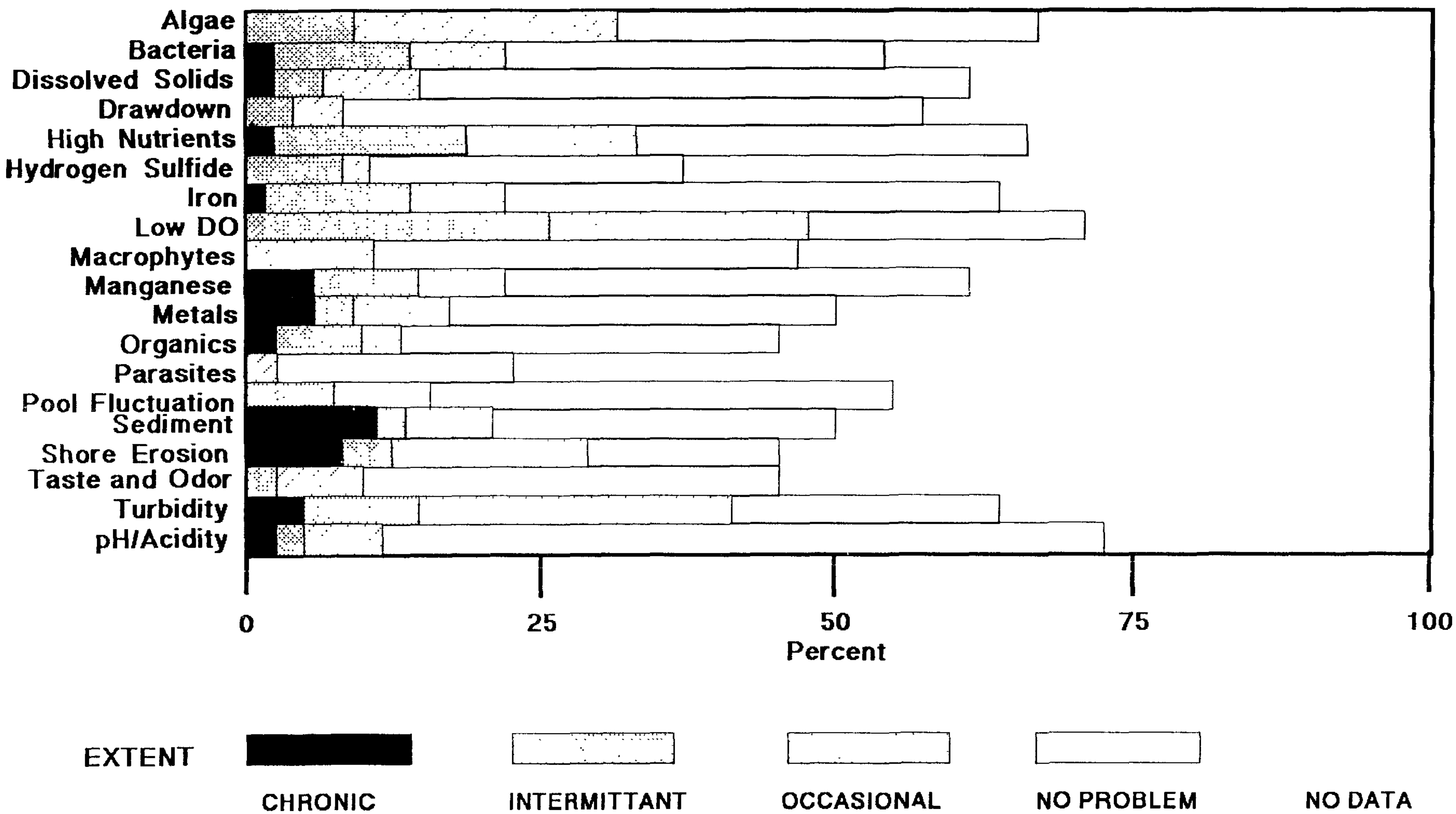



Figure VI-4 Frequency of Occurrence of Water Quality Conditions in COE Impoundments (N=46).

Most prevalent are concerns related to flow, the release of waters low in dissolved oxygen concentration, and the erosion and transport of sediment.

Extremes in flow and/or excessive changes in flow, which result from operational procedures required to meet authorized project purposes (e.g., flood control, power generation, etc.), may impact downstream uses.

Flow fluctuation, although not a water quality problem per se, is an important factor affecting water quality and use in tailwaters, and is frequently a key water quality management issue. Flow-related problems for tailwaters include higher than normal flows following flood events as retained flood waters are released, lower than normal flows during periods when pool storage is being increased, and daily fluctuations resulting from the operation of hydropower facilities, particularly when power is produced to meet peak-load requirements.

The loss of dissolved oxygen in the hypolimnia of reservoirs potentially results in direct and indirect impacts for tailwaters. For projects which, because of their structural or operational characteristics, do not allow for complete reaeration of release water as, dissolved oxygen concentrations below saturation may occur throughout part or all of the summer stratified season. Such is the case for approximately one-third of the COE projects inventoried here. However, the COE notes that only one of the 46 sampled projects experiences periodically severe dissolved oxygen conditions in its tailwater and that this project is a newly-filled reservoir where such occurrences are predictable and short-lived.

The occurrence of elevated concentrations of metals and nutrients in tailwaters is indicated for approximately 30 to 40 percent of the sampled projects for which such evaluations were made. And, as reported by the COE, these projects are primarily those for which reduced dissolved oxygen concentrations were reported. These projects are also reported to receive relatively high inputs of metals and nutrients from their surrounding watershed.

The transport of suspended sediment from reservoir to tailwater and/or the erosion and resuspension of bank and bed materials impacts tailwater areas below approximately 40 to 50 percent of the projects for which evaluations were provided. In most cases, impacts are minor and result from increased turbidity. In other cases, degradation of immediate downstream areas is indicated. Preliminary evaluation of information by COE suggests that, while project operation plays a significant role in the determination of release conditions, pronounced regional patterns in the distribution of such conditions are apparent. In general, reservoirs located in regions dominated by highly-erodible soils experience higher inputs of suspended sediment and, therefore, often release turbid waters.

An evaluation of water quality conditions in pools, also based on sampled responses to the questionnaire, are presented in Figure VI-4. Most prevalent were problems related to the eutrophication process. These include excessive nutrient concentrations, algal blooms, reduced water clarity, macrophyte infestations, and the loss of dissolved oxygen in bottom waters. Other conditions of concern include excessive concentrations of reduced iron and manganese in bottom waters, and the accumulation of sediment and contaminants. As was discussed for tailwaters, problematic conditions were identified for approximately 40 to 50 percent of the pools for which evaluations were available. And, again, varying degrees of severity in problematic conditions are apparent.

## TENNESSEE VALLEY AUTHORITY

### Background.

The TVA system of multipurpose dams encompasses more than 11,000 miles of shoreline and 940 square miles of surface water (see Figure VI-5). Construction was largely completed by the late 1950's. The primary purposes of TVA's projects are navigation, flood control, and electrical generation. The TVA system includes 33 large dams (29 hydropower and 4 nonpower) and additional smaller dams. Due to their age, the TVA impoundments are representative of mature reservoirs.

With the completion of the dam construction program, TVA has turned its attention to managing the reservoir system and promoting the proper growth, conservation, and management of the agency's natural resources. As part of this continuing effort, the TVA Board of Directors authorized in September 1987 the broadest reassessment in 50 years of the operating policies of its dams and reservoirs. The central issues being addressed

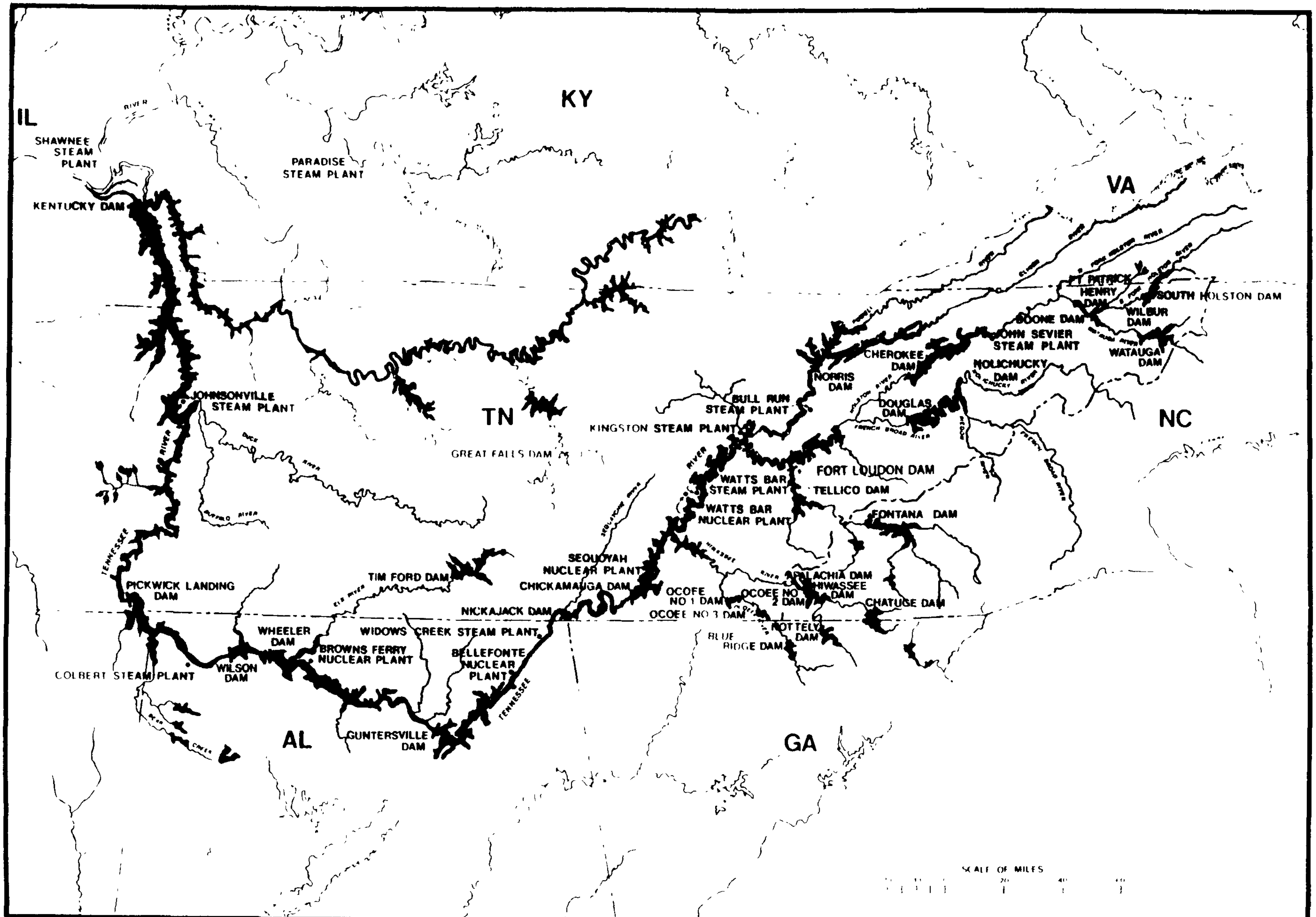



FIGURE VI-5 THE TENNESSEE VALLEY AUTHORITY'S MULTIPURPOSE WATER RESOURCE SYSTEM by the study are whether water quality and recreation should be added as primary purposes of TVA reservoir operations to the statutory purposes of navigation, flood control, and electrical generation. The study is being conducted in accordance with the procedures of the National Environmental Policy Act and will determine the long-term policies that should direct TVA efforts in reservoir system operations and river management into the next century. The current schedule calls for presentation of the final report and Environmental Impact Statement and the results of public review and comment of the recommendations in 1989.

<u>**TVA Water Quality Assessment**</u>.

Water quality conditions for reservoirs in the Tennessee Valley were assessed using the approach applied by the Corps of Engineers to assess its projects. Thirty-three projects were assessed, including all the hydropower projects and four nonhydro projects. Those projects not included are small projects for which no data were available. The results are presented in Figures VI-6 and VI-7 for pools and Figures VI-8 and VI-9 for tailwaters.

Water uses were severely impacted at several sites. Low dissolved oxygen, hydrogen sulfide, iron, and manganese are considered to be at sufficient levels that the fishery at Upper Bear Creek Reservoir is practically nonexistent. Other reservoir projects having severe use impairment are the three Ocoee River projects where sediment accumulation, iron, manganese, turbidity, and metal contaminants are adversely impacting aquatic life and recreation, primarily in Ocoee Number 3, with less impairment in Numbers 2 and 1. Finally, the Nolichucky Reservoir has been filled with sediment to the point that it is no longer considered a reservoir.

The results indicate that in reservoir pools the most significant impacts were pool level fluctuations and bacteria (about 50 and 30 percent of the reservoirs, respectively). The next most significant user impacts were turbidity, algae, macrophytes, sediment accumulation, and shore erosion, all of which occur at 15-20 percent of the reservoir project). Minor impacts, occurring at 20 percent or more of the reservoir projects, were related to the following parameters; iron, manganese, low dissolved oxygen, turbidity, low temperature, high nutrients and algae, macrophytes, sediment accumulation, pool level fluctuation, shore erosion, pH/acidity, bacteria, and fish parasites.

Several items worth noting for the analysis on TVA pools are:

(1) data on hydrogen sulfide were limited and the results of this analysis may change when more data becomes available;

(2) several parameters had high rates of recurrence with the potential to impact uses in the future: i.e., high nutrients, sediment accumulation, and shore erosion;

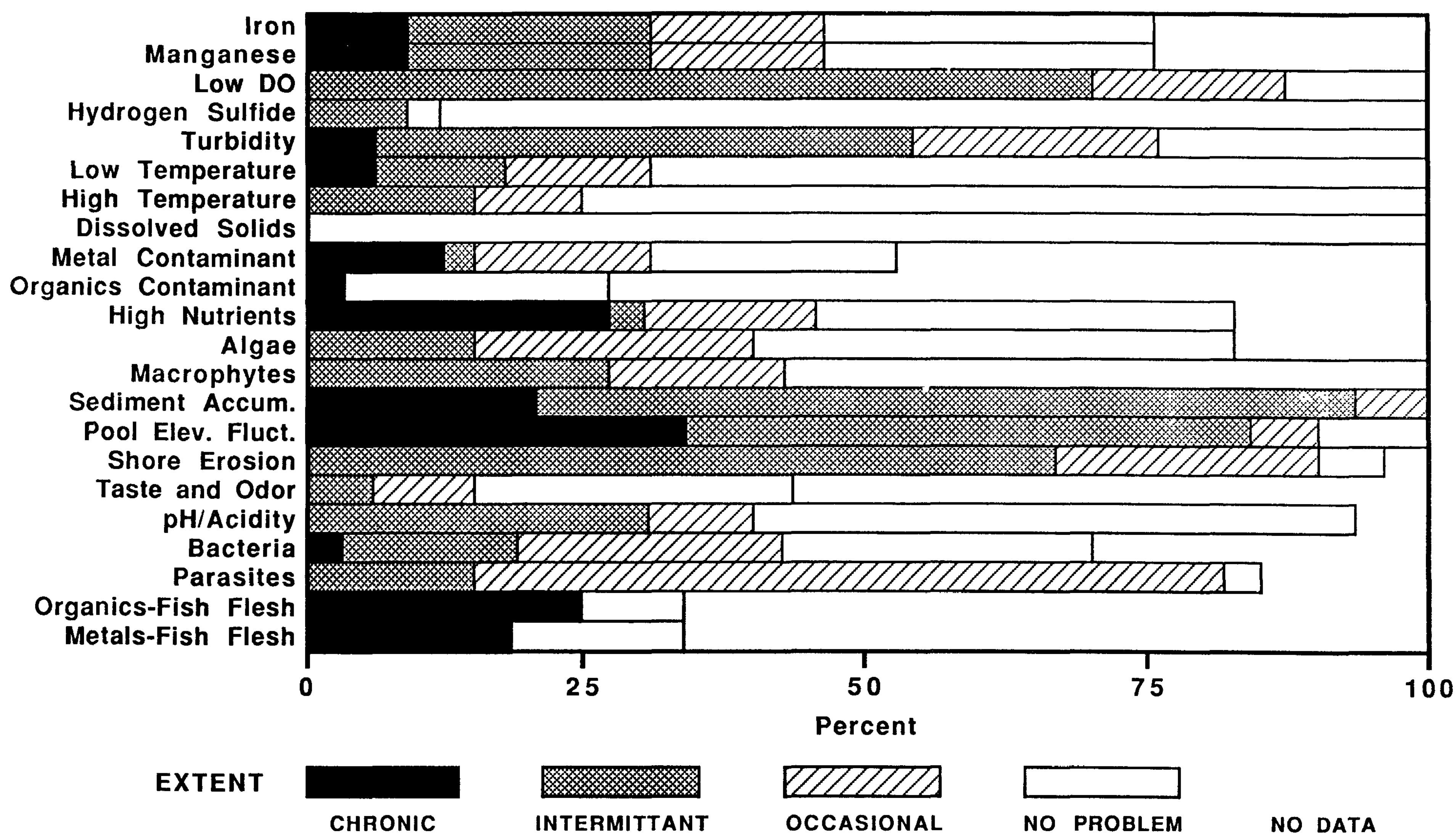



FIGURE VI-6 **Frequency of Occurrence of Water Quality Conditions in TVA Reservoir Pools (N = 33).**

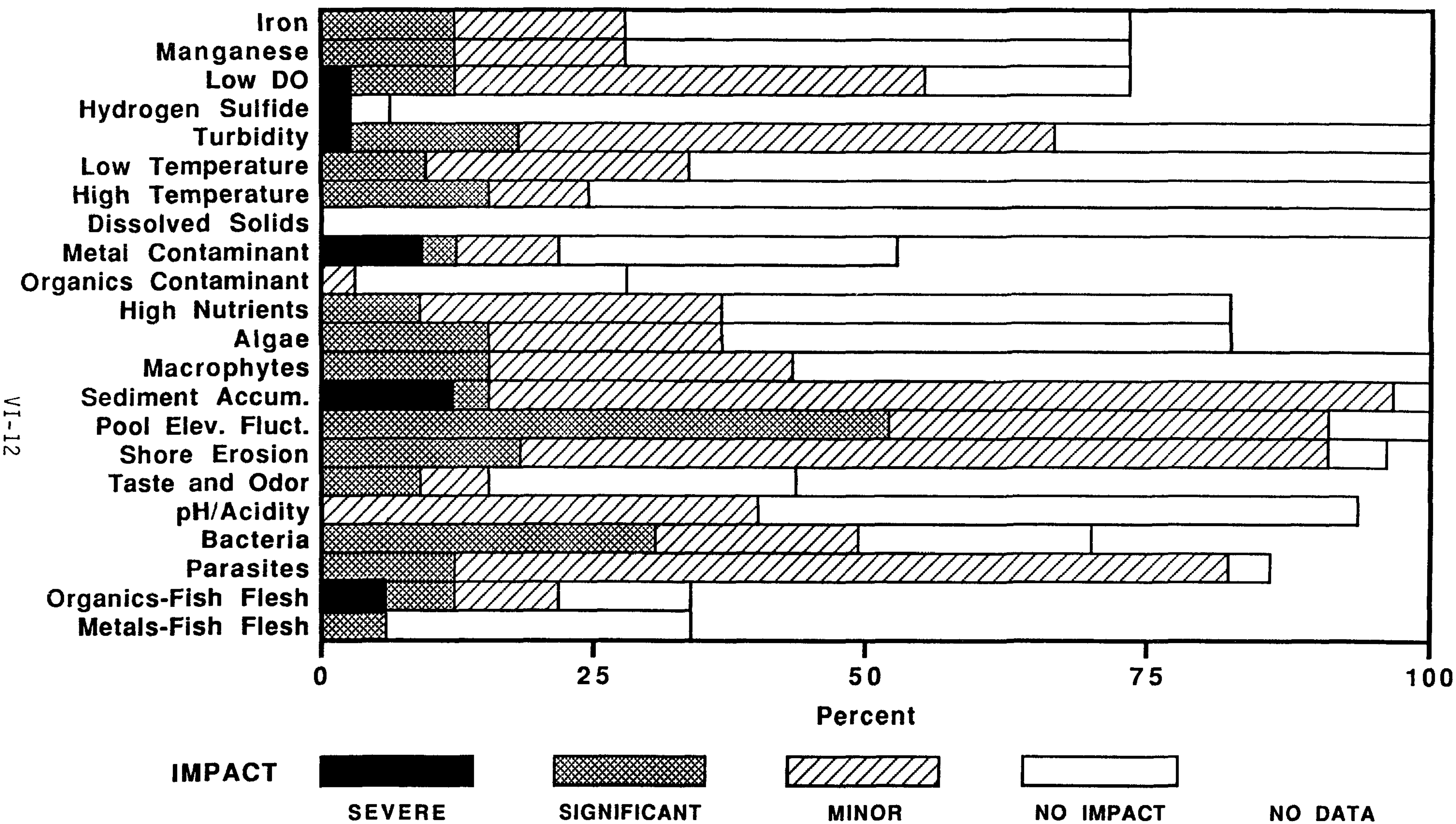



FIGURE VI-7 **User Impact Assessment for TVA Reservoir Pools (N = 33).**

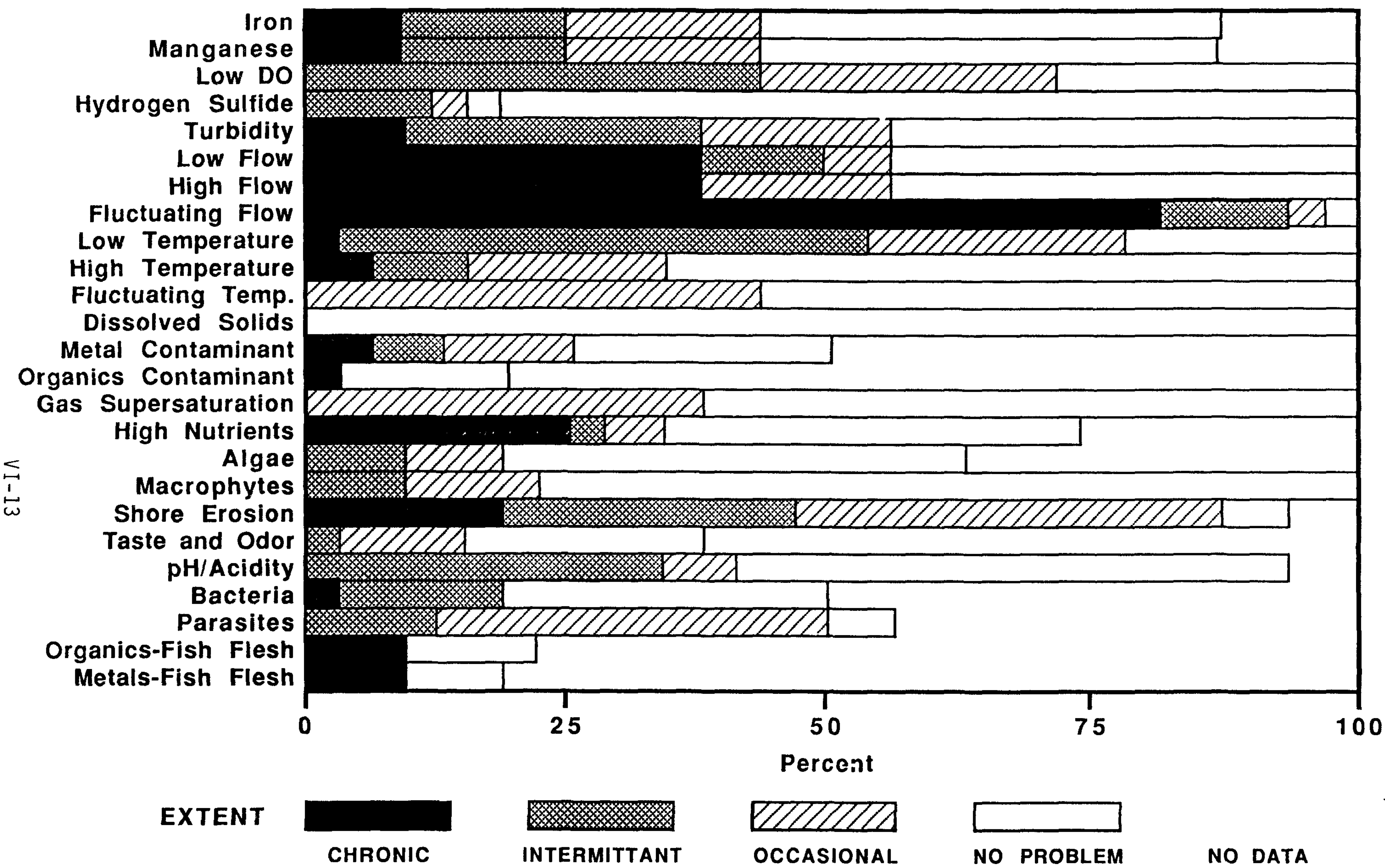



FIGURE VI-8 Frequency of Occurrence of Water Quality Conditions in TVA Tailwaters (N = 33).

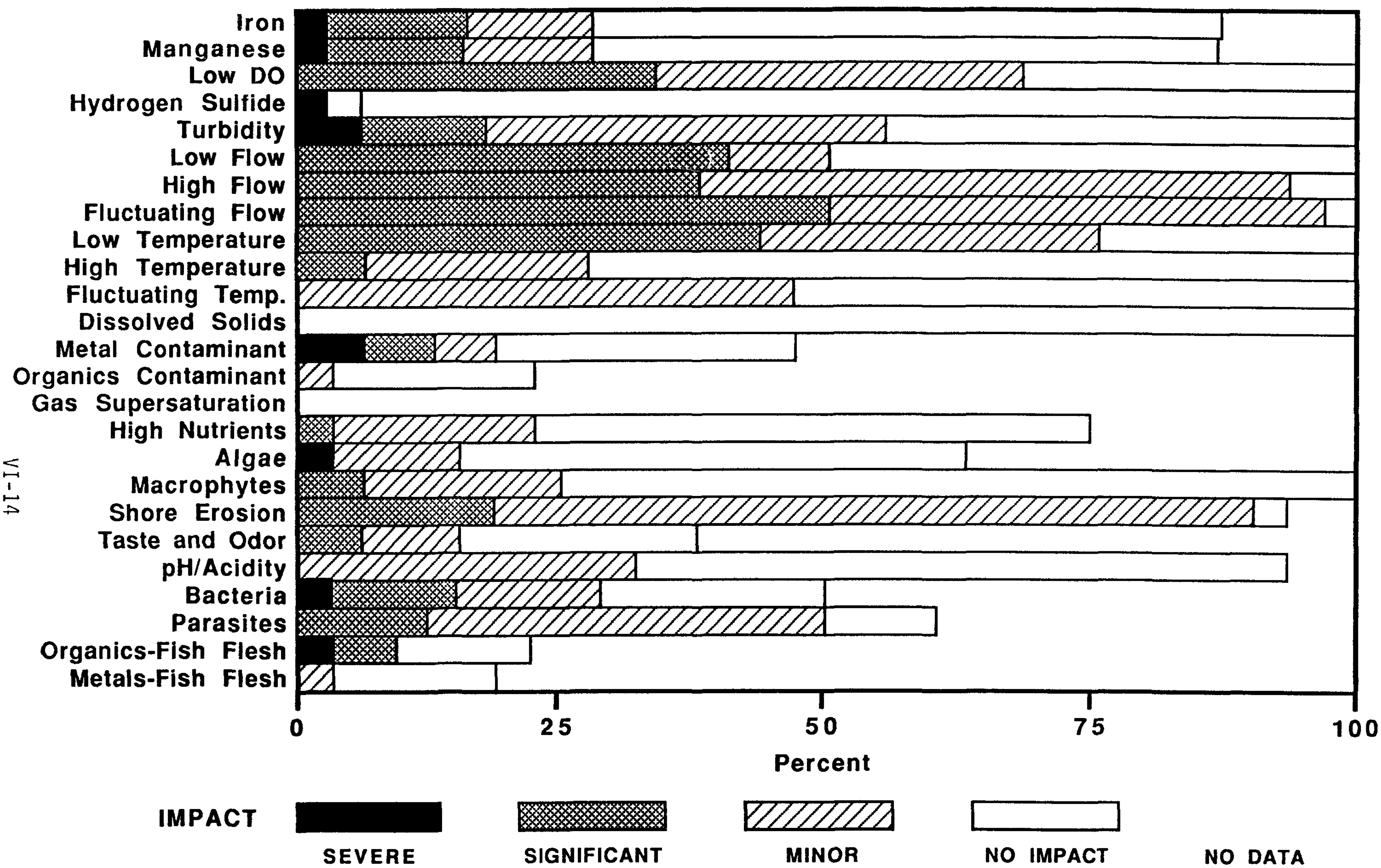



FIGURE VI-9 **User Impact Assessment for TVA Reservoir Tailwaters (N = 33).**

(3) low dissolved oxygen seasonally occurred in about 70 percent of the reservoirs, but user impacts were considered minor for most projects because the condition was restricted to the hypolimnion or bottom waters of the reservoir; and

(4) more data are needed on organics and metals in fish flesh.

For reservoir tailwaters, the results indicate that the most significant impacts resulted from low dissolved oxygen, streamflow (high, low, and fluctuating), and low temperature. The next most frequent user impacts were associated with iron, manganese, hydrogen sulfide, turbidity, metal contaminants, streambank erosion, bacteria, and fish parasites. All of these parameters occurred at about 15-20 percent of the projects. It should be noted that the questionnaire approach for this assessment did not differentiate between the significance of physical and chemical parameters; therefore, it did not reveal that chemical problems generally have more serious impacts on uses. The most frequent minor impacts, occurring at 20 percent or more of the projects, were related to the following parameters: low dissolved oxygen, turbidity, high flow, fluctuating flow, low temperature, high temperature, fluctuating temperature, streambank erosion, and parasites in fish.

## THE BUREAU OF RECLAMATION

### Background.

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the western United States and Hawaii. In most areas of the 17 western states, which constitute the main area served by the USBR, less than 20 inches of moisture fall each year. However, several important rivers, fed mainly by the melting snow packs in the mountains, flows through these states. A basic function of USBR is to harness these streams and to store their surplus waters in times of heavy runoff for later use when the natural flow is low. USBR water impoundment project purposes cover a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river regulation and control; fish and wildlife enhancement; and outdoor recreation.

Reclamation project facilities in operation during 1986 included: 349 storage reservoirs; 50 hydroelectric power plants; 288 circuit miles of transmission lines; 15,804 miles of canals; 1,382 miles of pipelines; 276 miles of tunnels; 37,263 miles of laterals; 17,002 miles of project drains; 240 pumping plants; and 254 diversion dams. Over 20.5 million people receive municipal and industrial water, 13.8 million kilowatts of installed hydroelectric power capacity exists, nearly 10 million acres of western farm land receive full or supplemental irrigation, and 53.2 million visitor days of recreation are recorded annually.

Completed water service facilities are transferred to local water user organizations for operation and maintenance as soon as the organizations become capable of assuming these functions. USBR operates and maintains hydroelectric power plants and some water storage and supply works on multipurpose projects.

**USBR Water Quality Assessment.**

Information on water quality conditions and user impacts for all USBR storage reservoirs and tailwaters was solicited by distributing the questionnaire to all six Bureau regional offices. All regions responded, and a total of 250 questionnaires were returned. The geographical distribution of this response by state is shown in Figure VI-10. Since there are approximately 349 USBR storage reservoirs in 17 western states and Hawaii, this response represents nearly 72 percent of the total.

Information obtained on the frequency of occurrence of various water quality conditions in USBR reservoirs and their impact upon user benefits are summarized in Figures VI-11 and VI-12, respectively. Tailwater conditions and their impacts are shown in Figures VI-13 and VI-14, respectively.

What is most immediately apparent in these four figures is that in an average of 54 percent of the reservoir cases and 59 percent of the tailwater cases, there are no data upon which to make an evaluation of the conditions or their impact on user benefits. Water quality data are usually only collected on a particular USBR project when some problem is noted or suspected, or when some change in the structure or operation is contemplated. Consequently, the picture of water quality conditions in Bureau reservoirs and tailwaters given by the available information is probably somewhat skewed toward those situations where some problem is perceived or an impact is felt. The following assessment is, therefore, probably conservative.

USBR data suggest that the main conditions affecting user benefits in Bureau reservoirs are drawdown, pool fluctuation, turbidity, sediment, and shore erosion. These conditions arise from the way water storage reservoirs are operated in an arid climate, where spring snowmelt or winter rains are the major source of runoff, and drawdown is continuous throughout the long dry season. Drawdown was rated as having a severe impact on user benefits in six USBR impoundments, and a significant impact in 33 others, out of a total sample of 107 reservoirs with information available. Thus, the cumulative percentage of reservoirs with data in which drawdown was rated as having at least a significant impact on user benefits is 36 percent. Corresponding cumulative percentages for the other four conditions are: pool fluctuation 35 percent, turbidity 13 percent, sediment 13 percent, and shore erosion 10 percent. The last condition, shore erosion, had no severe impact ratings out of a total of 108 impoundments rated.

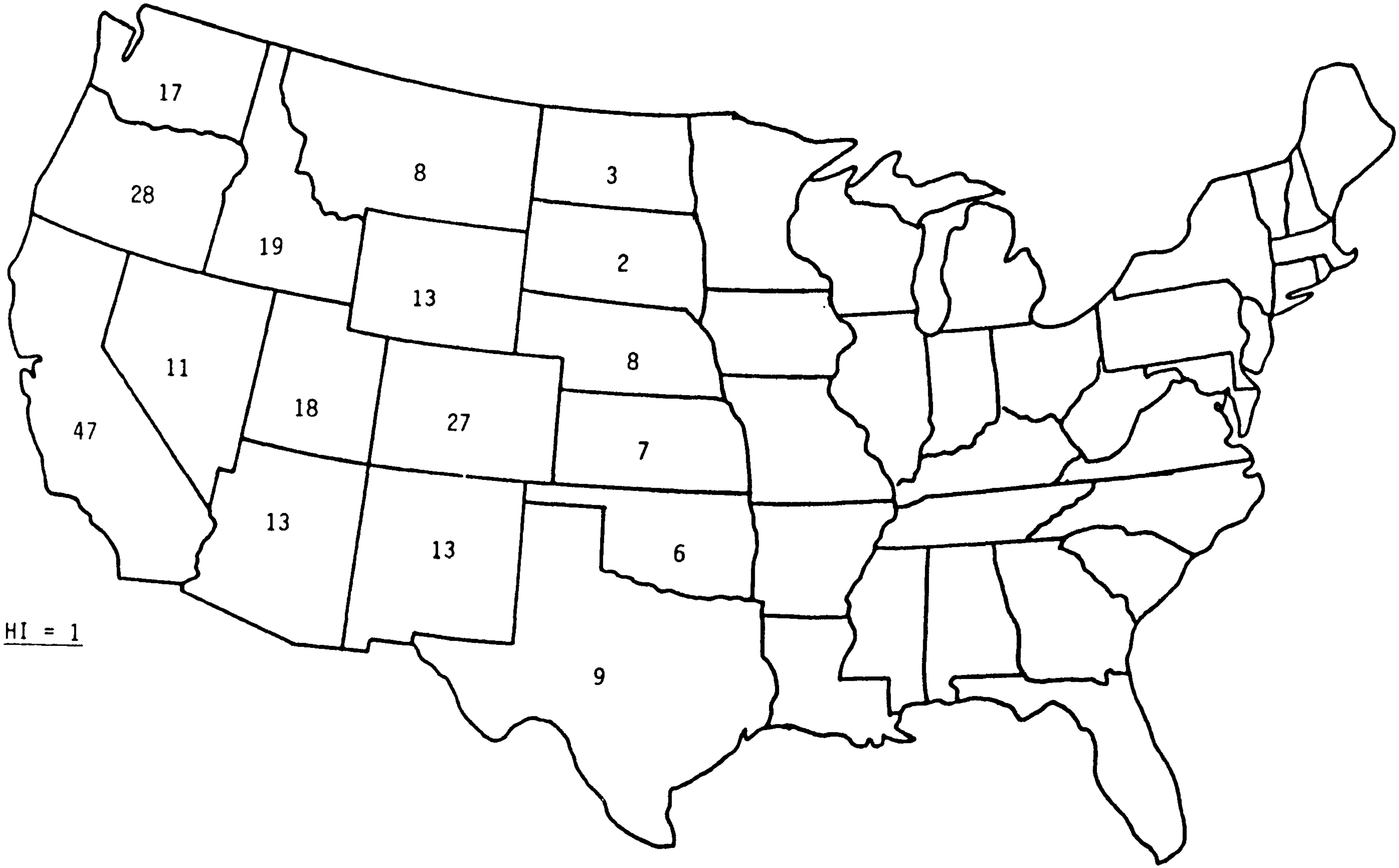



FIGURE VI-10 - Geographic Distribution of Responses to Water Quality Assessment of Bureau of Reclamation Reservoirs by State (Total - 250)

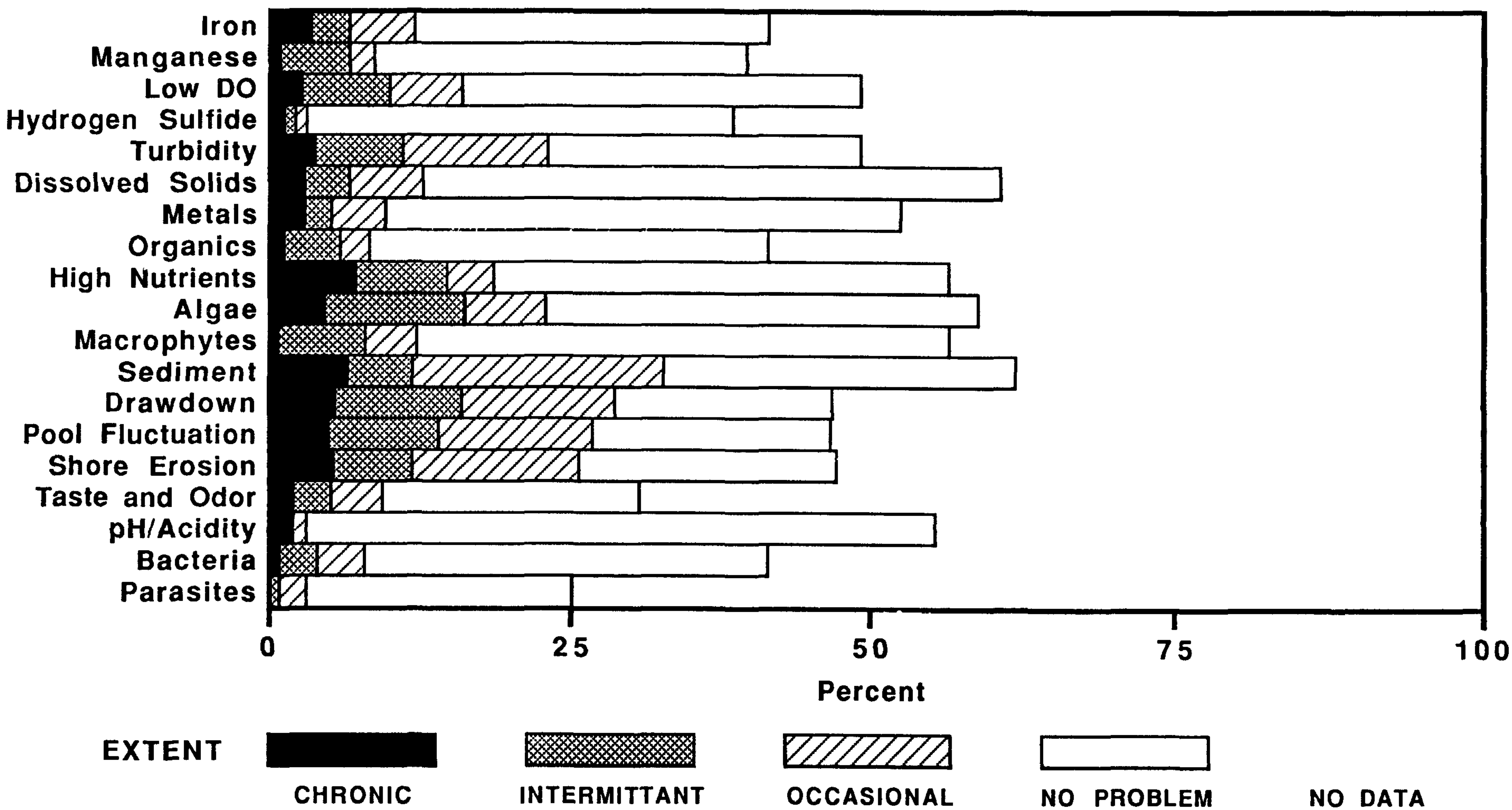



FIGURE VI-11 **Frequency of Occurrence of Water Quality Conditions in USBR Reservoirs (N = 250)**

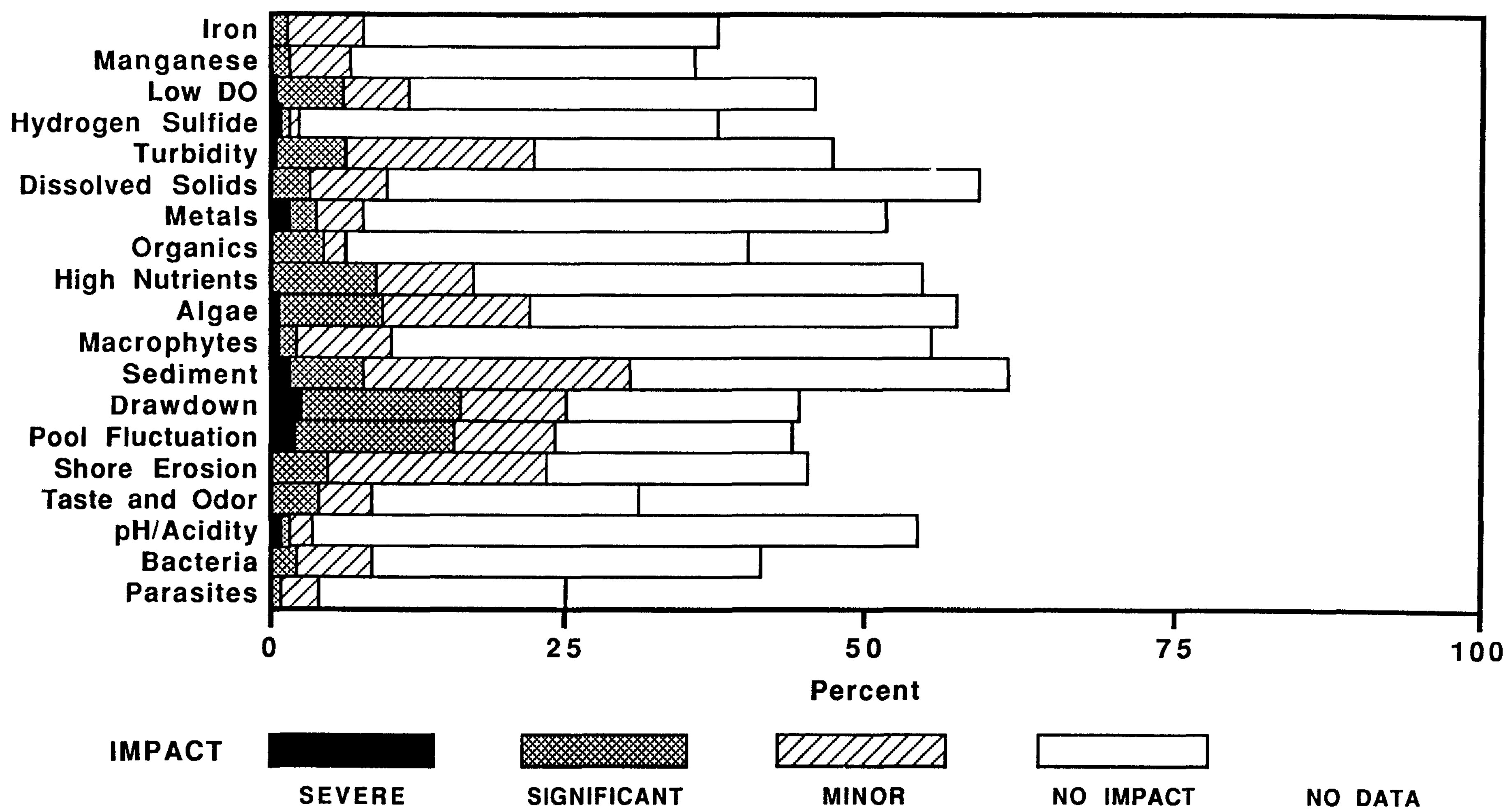



FIGURE VI-12 **User Impacts of Water Quality Conditions on User Benefits at USBR Reservoirs (N = 250)**

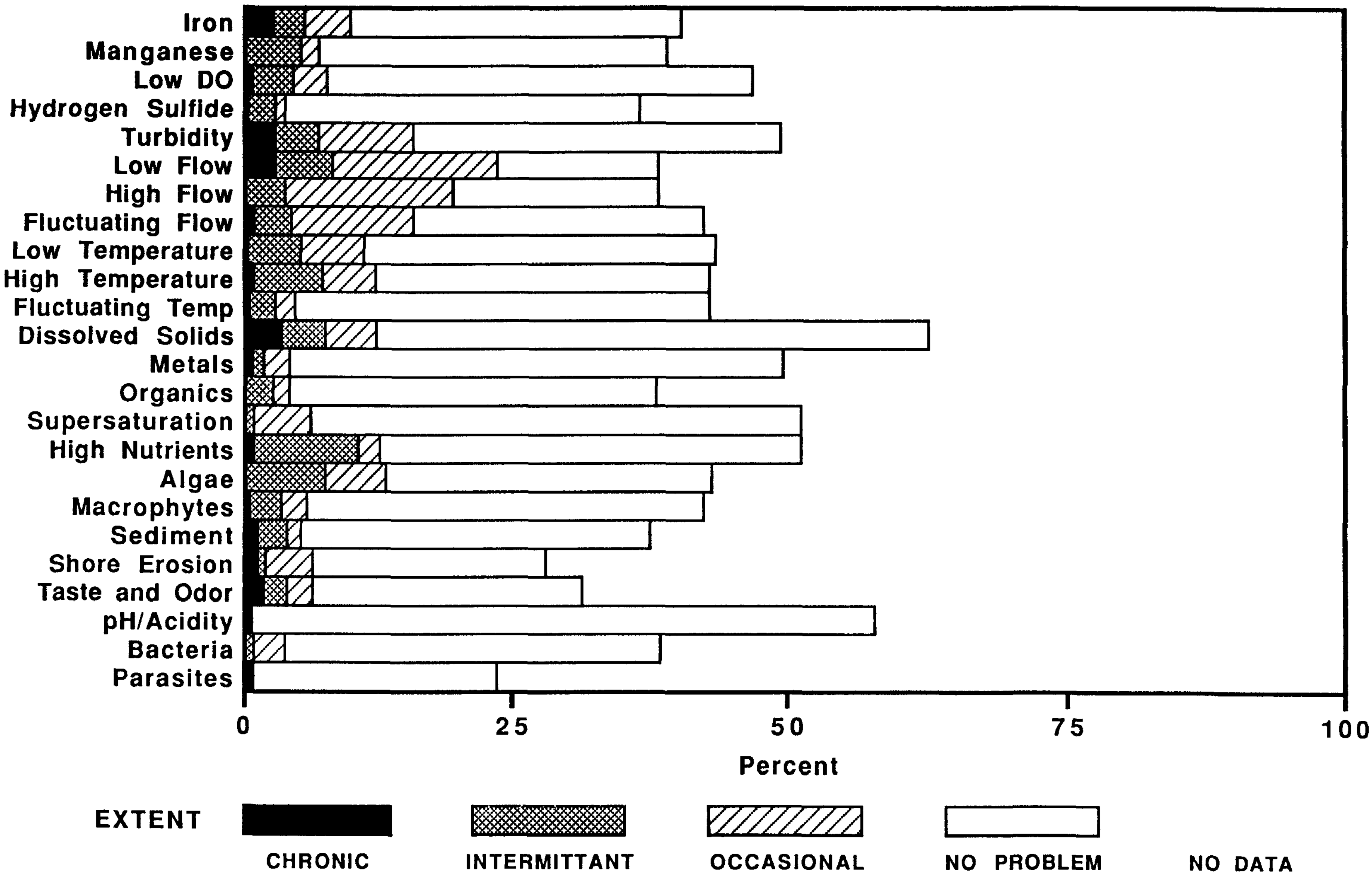



FIGURE VI-13 **Frequency of Occurrence of Water Quality Conditions in Tailwaters of USBR Reservoirs (N = 250)**

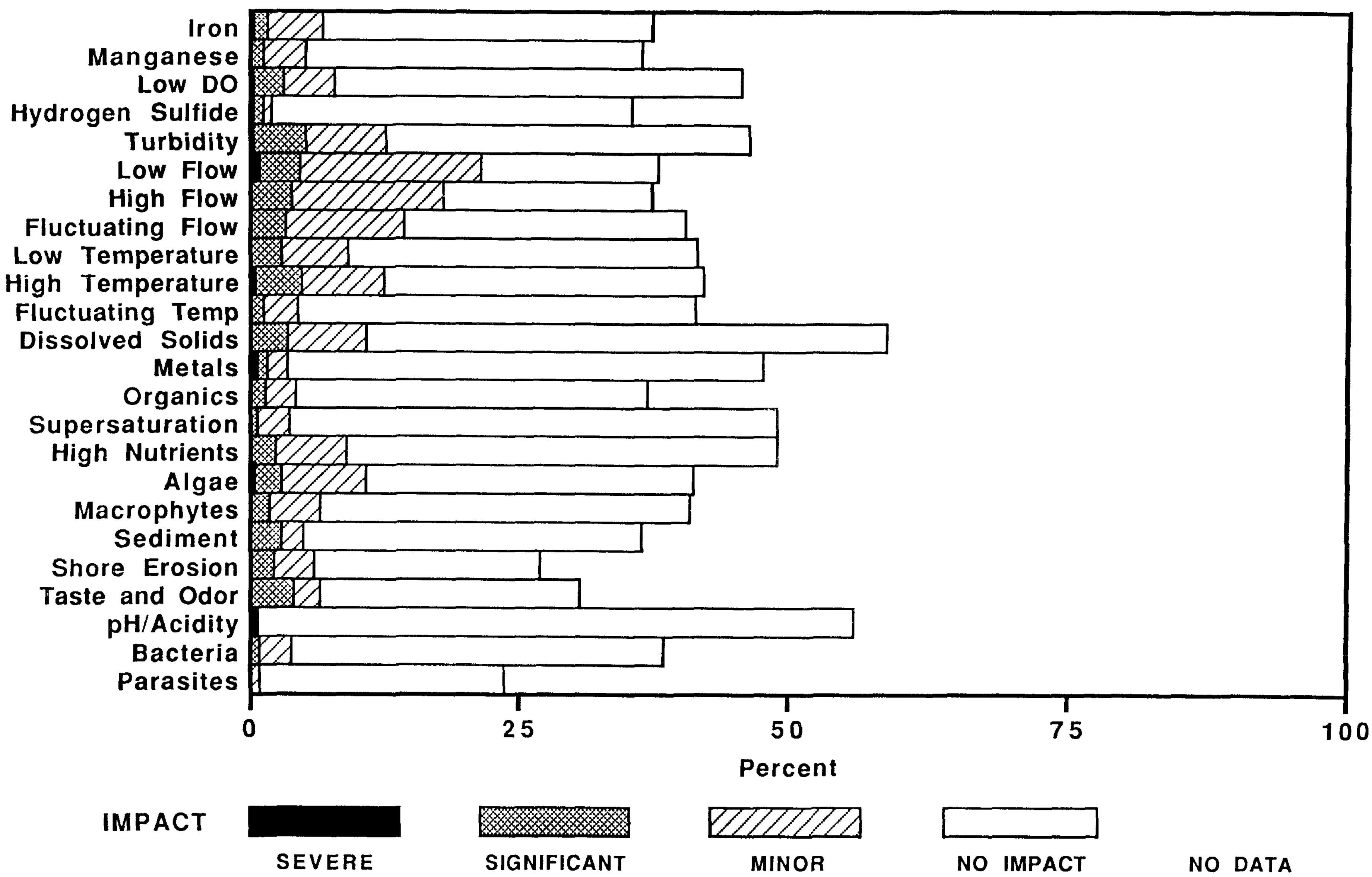



FIGURE VI-14 **Impacts of Water Quality on User Benefits at USBR Tailwaters (N = 250)**

The second most important set of reservoir water quality conditions affecting user benefits are related to eutrophication: algae, high nutrients, low dissolved oxygen, and taste and odor problems. Cumulative percentages of reservoirs with data where these conditions were rated as having at least significant impacts on user benefits were: algae 17 percent, high nutrients 15 percent, low dissolved oxygen 14 percent, and taste and odor problems 12 percent. There were no severe impact ratings for high nutrients or taste and odor problems, however.

Although iron is often present in USBR reservoirs, it was rated as having at least a significant impact on user benefits in only 4 percent of the rated reservoirs. In fact, it should be noted that only drawdown and pool fluctuation were perceived as having really significant impacts on reservoir user benefits.

Tailwater conditions and user impacts are depicted in Figures VI-13 and VI-14, respectively. Here again, the major impact-producing conditions seem to cluster around the mode of operation of water supply reservoirs in an arid region: high flow, low flow, turbidity, and high temperature. Of these, high flow was rated as having significant user impacts in 21 percent of the tailwaters with data, but in no case was it rated as having a severe impact. The other three conditions were rated as having at least a significant impact in 13 percent, 12 percent, and 11 percent of the rated tailwaters, respectively. Taste and odor problems were rated as significant in 13 percent of the tailwaters with available data, but were not considered severe in any case.

**OVERVIEW**

The Corps of Engineers (COE), Tennessee Valley Authority (TVA), and U.S. Bureau of Reclamation (USBR) each prepared an assessment of known water quality conditions at their water impoundment projects. These assessments are based on a questionnaire completed by Agency personnel familiar with the water quality conditions at each project. The result is a subjective data base for each Agency, presenting the frequency of occurrence of specified water quality conditions and their relative degree of impact to user benefits. Parameter-specific data were not available for a large percentage of the projects responding to the questionnaires. Also, it is likely that existing water quality data were collected primarily at projects where some problem was noted or suspected. Consequently, the available data on water quality conditions may be skewed, introducing a pessimistic bias. It is, therefore, difficult to project results of these assessments to each Agency's population of impoundments.

The water quality conditions described in the results of the agencies' questionnaire survey are a mix of conventional water quality parameters (e.g., low dissolved oxygen, pH, turbidity, taste and odor, bacteria, nutrients, dissolved solids, metals, and organics) and chemical and physical parameters of specific interest to impoundments (e.g., iron, manganese, hydrogen sulfide, temperature, algae, sediment accumulation, pool level fluctuations, and shore erosion). The physical parameters are reported as occurring with greater frequency and at higher levels of impact than the chemical parameters. Pool and tailwater fluctuations; high and low flows; erosion, sediment transport, and sediment accretion were the primary physical water quality problems reported. It is not known whether the physical parameters are actually more problematic or whether, in view of the lack of hard monitoring data on chemical water quality, the more visible physical parameters are simply easier to detect and report subjectively. For the TVA system, even though physical concerns are more prevalent, chemical concerns are generally more serious when they occur.

Low dissolved oxygen in pool hypolimnia appears to be a seasonal concern primarily in projects located in the eastern half of the country. Low dissolved oxygen occurred as at least an intermittent problem in 47 percent of the COE reservoirs, 70 percent of TVA's reservoirs, and only 9 percent of USBR's reservoirs. Tailwaters experienced similar results, with low dissolved oxygen reported as at least an intermittent problem in 25 percent of COE's tailwaters, 38 percent of TVA's tailwaters, and only 4 percent of USBR's tailwaters. The USBR assessment showed that problems of low DO, dissolved iron and manganese, and hydrogen sulfide are relatively rare at Bureau dams, although summer thermal stratification is nearly universal and low level outlets are not uncommon. Some major differences between these reservoirs and southeastern reservoirs, where low DO problems may be more prevalent, are that the western reservoirs are, on the average, less eutrophic (i.e., lower BOD), more rapidly flushed, and subject to shorter thermal stratification periods. In general, the factors which are involved here include an arid climate, relatively low inflow nutrient concentrations, a lower intensity of development in the watersheds, and a wider range of seasonal water temperature fluctuations. The size and depth of most Bureau reservoirs are not substantially different from those in the southeast, however.

Coincident with the loss of dissolved oxygen from pool hypolimnia is the increased release of dissolved materials from bottom sediments. Iron, manganese, and hydrogen sulfide often appear in elevated concentrations in the tailwaters of projects with low dissolved oxygen; the COE assessment reports a clear link in these parameters where data were available. TVA noted that iron, manganese, and hydrogen sulfide appeared in 50 percent of their projects with low dissolved oxygen.

The COE assessment reports pronounced regional patterns in the distributions of some water quality conditions. For example, reservoirs located in areas with highly erodible soils experience greater sediment loads and generally experience greater problems with turbidity in tailwater releases and sediment accretion in the pool. Similarily, reservoirs experiencing high nutrient and/or metals inputs from the surrounding watershed typically reported more problems with eutrophication, low dissolved oxygen, and other related issues in both pool and tailwaters. Many of the results reported by TVA and USBR can also be explained by regional/local influences of land use, geology, topography, and climate.

## VII. CONCLUSIONS

This report addresses general issues of water quality effects associated with impoundment of water by dams. It attempts to estimate the character and national extent of these effects through a literature review and analyses conducted on a random sample of a partitioned data base population of 68,155 dams. Insufficient data were collected to draw quantitative conclusions pertaining to small dams (less than 10,000 acre•feet normal storage volume) and to a large degree, large nonpower dams (at least 10,000 acre•feet of normal storage volume and no reported power generating capacity). Quantitative and qualitative conclusions are drawn for large power dams (greater than 10,000 acre•feet of normal storage volume and 100 kilowatts or more of installed power). General conclusions regarding likely water quality effects are derived from the literature review. Specific conclusions are based on the results of the four EPA analyses. Three federal agencies, the U.S. Army Corps of Engineers (COE), the Tennessee Valley Authority (TVA), and the U.S. Bureau of Reclamation (USBR) conducted independent assessments of water quality conditions at their respective water resource projects. Due to the complex interrelationships of the potential water quality effects, the numerous variables affecting impoundment water quality, and the lack of sufficient detailed information, it is difficult to draw accurate conclusions regarding the national extent of water quality effects attributable to impoundments.

This study is limited in estimating the national extent of dam water quality primarily because of a lack of monitoring and descriptive data. The **STO**rage and **RET**rieval data base (STORET) was used as the primary source of monitoring data. Although quite extensive, data were not available for many of the sites randomly selected for analysis. Other descriptive data, such as the type of outlet structure, watershed land use, and other influences on water quality, were also not available for this study. Additional monitoring data, descriptive data, and a larger random sample of dams would probably extend the study's findings.

Impoundments are created for a variety of purposes that provide important social, economic, and aesthetic benefits. Most projects serve multiple purposes, and it is important to recognize impoundment benefits and purposes in evaluating their water quality consequences. Among the project purposes recognized in this report are: hydropower generation including pump storage, navigation, flood control, water supply, conservation, recreation, fish and wildlife maintenance, water quality enhancement, and low flow augmentation. Operating impoundments to achieve multiple purposes is often complicated by conflicting requirements for water flow and quality. Water quality within the reservoir is dependent upon watershed land use, point sources, project design, depth, season, and climate. Water quality in the tailwater depends on the depth of water withdrawal, project design, configuration of the tailwater channel, and local atmospheric conditions.

During the past 20 years, there has been a growing awareness of the importance of water quality for water resources development and management. This has resulted in major changes in the policies and practices of Federal agencies, state and local agencies, private water developers, and the related professions. Active research programs on water quality have been initiated and carried out and coordinated. As a result, the planning, design, and operations of dams show an enhanced consideration of water quality. This trend should be encouraged to continue.

## WATER QUALITY EFFECTS OF IMPOUNDMENTS

Impoundment of free-flowing water by dams may potentially create several effects, both positive and negative, on water quality within the pool and downstream. Although this report focuses on unwanted effects, desirable changes, such as a reduced sediment load, may also result. The potential effects are often interdependent. Altering one condition in an impoundment may create a ripple of effects throughout the reservoir-stream ecosystem.

Impoundments can modify the physical, chemical, and biological characteristics of the free-flowing aquatic ecosystem. Physical and chemical characteristics in impoundments are also related to depth, volume, climate, watershed land use, geographic location, reservoir siting, and the schedule of water releases. Biological characteristics are related to the type of habitat. The magnitude of effect of the dam on water quality of releases appears related to the type of reservoir and to the design and operation of the impoundment.

Effects can generally be characterized in three categories: stratification-related, eutrophication, and other changes. Thermal stratification of reservoirs results in warm waters of the epilimnion (surface waters) overlying cooler and therefore denser waters of the hypolimnion (bottom waters). Deeper impoundments with poor mixing characteristics tend to stratify. Compared to waters upstream of the impoundment, the waters of the epilimnion may tend to have slightly higher temperatures and somewhat lower nutrient concentrations. Waters of the hypolimnion, on the other hand, tend to have much lower temperatures and lower dissolved oxygen levels.

When low concentrations of dissolved oxygen (e.g., anoxic conditions) occur in the hypolimnion of reservoirs, this can result in the formation of reduced forms of iron, manganese, sulfur, and nitrogen. The reduced forms of these compounds can adversely affect water quality and may be detrimental to aquatic life. These compounds are converted to more assimilable compounds in oxidizing environments, such as the epilimnion and tailwaters with adequate dissolved oxygen concentrations. Well-mixed, unstratified reservoirs seldom experience problems with iron, manganese, sulfur, or nitrogen compounds.

Eutrophication is a naturally-occurring process involving increased growth and death rates of aquatic plants as well as sediment accumulation, and is typically associated with reservoir aging. Excess nutrients (especially nitrogen and phosphorous) in an impoundment can increase eutrophication to undesirable levels. The settling and decay of excess aquatic vegetation can deplete dissolved oxygen levels in the hypolimnion, leading to anoxic conditions.

Water quality conditions in impoundment tailwaters are determined by water quality in the reservoir and design and operation of the project outlet works. For stratified impoundments, a primary determinant of downstream water quality is whether a dam's outlet releases waters from the epilimnion or the hypolimnion. With respect to temperature, release of cool hypolimnetic waters, if done consistently all summer, can have a desirable effect on downstream fisheries in many parts of the country. However, low dissolved oxygen concentrations in the released hypolimnetic waters may limit its ability to support some aquatic life.

Thus, the effects of stratification, possibly compounded by eutrophication, are passed downstream via the discharge conduits. If the outlets are at a low level, colder, possibly low dissolved oxygen, waters are released. If the outlets are at a surface spillway, or downpipe, warmer waters are discharged and the dissolved oxygen levels tend to be higher because of turbulence and splash and also because of possible algal photosynthesis in the summer. Power dams frequently have low outlets. Large nonpower and small dams are less likely to have such outlets because project purposes do not require their use. If a low-level outlet exists as part of a large nonpower dam, reaeration typically takes place in the process of energy dissipation associated with reservoir releases.

Other water quality effects are generally considered to be less predominant than eutrophication and stratification-enhanced effects. Supersaturation of gases can occur as the result of rapid pressure changes in spillway discharges plunging into deep stilling basins, and may cause fish to suffer from gas bubble disease. Reservoirs, by virtue of surface evaporation, and in some cases the acceptance of return flows, may experience elevated salinity concentrations. The capture of sediment behind an impoundment and changes in erosion patterns downstream may also have an effect on water quality. Dams and their operations usually alter the "natural" flow patterns. This effect may be desirable or undesirable. Reaeration denial, where it occurs, deprives downstream waters of dissolved oxygen which would have been generated in the absence of the impoundment.

Reservoirs with short hydraulic residence times have reduced impacts on tailwaters because the water is discharged before the effects of impoundment are well established. Reservoirs with long hydraulic residence times act as settling basins, removing suspended material from inflowing waters. Pollutants and nutrients adsorbed to the sediments are also removed, settling to the bottom of the reservoir.

## RESULTS OF EPA ANALYSES

Four analyses were conducted in an attempt to estimate the national scope of the water quality effects. Information on small and large nonpower impoundments was limited, and no quantitative conclusions could be reached through the analyses regarding the effects of these two categories of dams except for the mixing analysis for large nonpower dams. The investigative information that is available pertaining to large nonpower and small dams is presented in the appendices. The results of the four analyses - mixing, tailwater dissolved oxygen, upstream/downstream comparison, and phosphorus enrichment - are presented in the following paragraphs.

The entire study population of 68,155 impoundments were analyzed for their mixing potential. Froude numbers were used as an index to determine an impoundment's tendency to thermally stratify. Impoundments that are strongly mixed are unlikely to have adverse water quality effects on tailwaters, whereas unmixed or stratified impoundments may be vulnerable to adverse water quality effects, which may be transferred downstream by low-level outlet structures. It is estimated that 40 percent of the large (over 10,000 acre•feet) power impoundments are potentially stratified as shown in Figure VII-1. For large nonpower impoundments, 37 percent are potentially stratified. Of these potentially stratified impoundments, some will experience water quality effects and some will not.

The second analysis was the comparison of dissolved oxygen levels in tailwaters below power impoundments. Dissolved oxygen levels were compared with a criterion of 5 mg/l for winter and summer data and regional data. Data were not statistically representative so that it was not possible to estimate dissolved oxygen levels on a national basis, but for the sample as shown in Figure VII-2, two relationships were established:

- Dissolved oxygen in power dam tailwaters during the summer have a much greater probability of not meeting a criterion of 5 mg/l than during winter.

- Larger power generating facilities show a greater probability of not meeting a dissolved oxygen criterion than do smaller power generating facilities.

However, these are general relationships and should not be applied directly to individual impoundments without recognition of site-specific conditions.

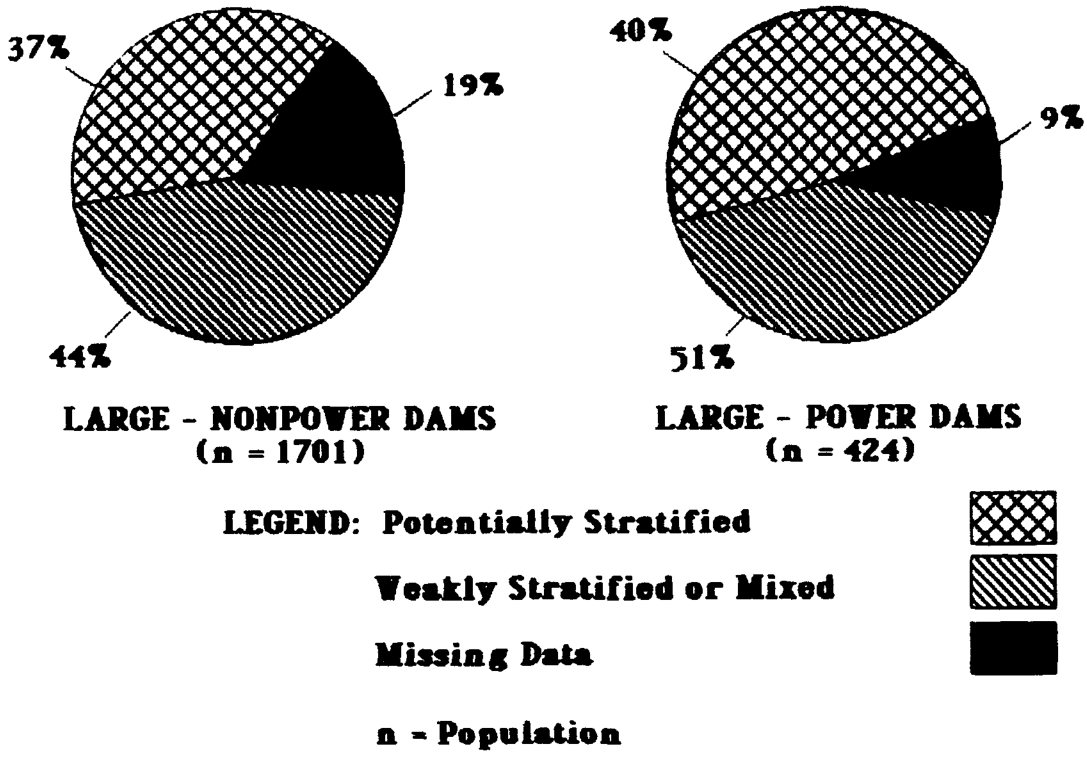



**Figure VII-1**
**Percentages of Mixing Tendency**

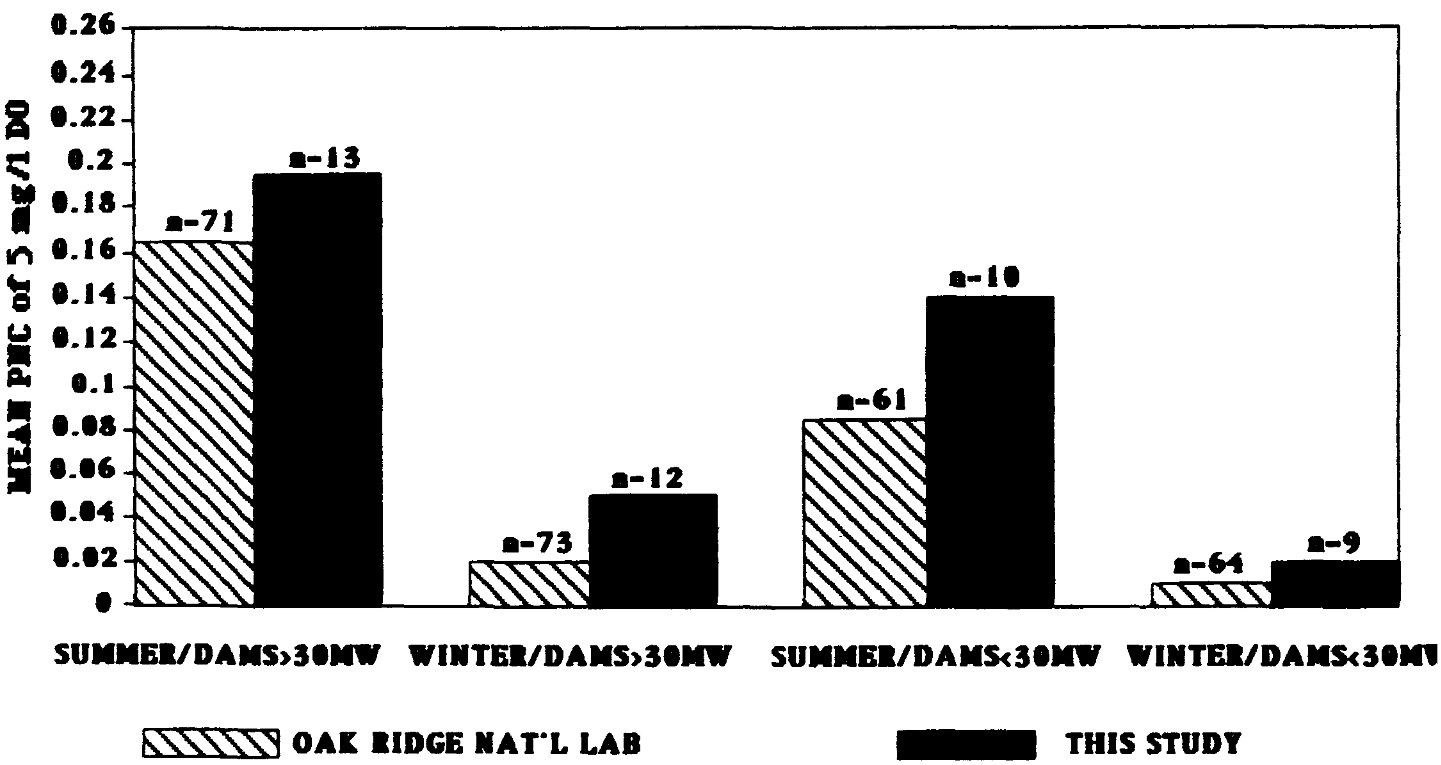



**Figure VII-2**
**Probabilities of Non-compliance (PNC)**
**with 5 mg/l Dissolved Oxygen (DO)**

The third analysis was an attempted comparison of upstream and downstream concentrations of temperature, dissolved oxygen, iron, manganese, phosphorous, and nitrogen. The analysis focused on a random sample of 40 impoundments from the 424 large power impoundments. Because only half of the sample had data on temperature, dissolved oxygen, phosphorous, and TKN, findings are limited to wide ranges applicable to the sample as follows:

- Between 28 percent and 55 percent of large power impoundments are likely to increase downstream temperatures and between 13 percent and 40 percent are likely to decrease annual average downstream temperature.

- Between 23 percent and 50 percent are likely to cause decreased dissolved oxygen levels in the tailwaters. Between 15 percent and 42 percent are likely to cause increased dissolved oxygen levels in tailwaters.

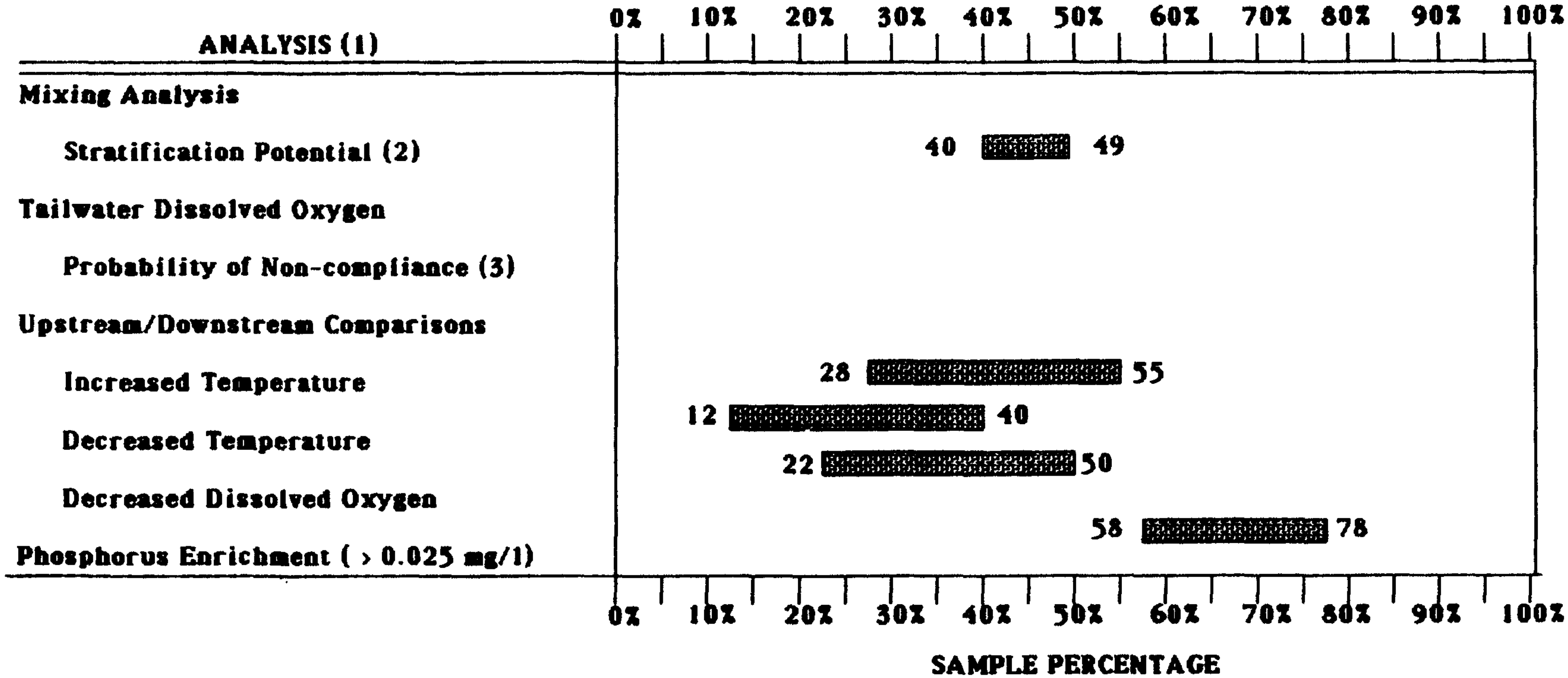
- Data were also collected for large nonpower and small dams, but success was limited to a minority of sites. The results of these efforts are summarized in the appendices.

The fourth analysis estimated phosphorous enrichment within impoundment pools, which is a potential indicator of eutrophication. This indicator is limited by a lack of information on light availability, hydraulic retention time, and other site-specific characteristics. Phosphorous levels were--both observed and estimated--compared against a guidance value of 0.025 mg/l as a means of describing high and low potential for enrichment. This analysis was conducted with a random sample of 40 large power dams (population of 424). The sample of large power dams showed 58 to 78 percent with phosphorous levels above 0.025 mg/l. Data were insufficient for similar analyses of large nonpower and small impoundments. A summary of some of the more important results appears in Figure VII-3.

## AGENCY ASSESSMENTS

The U.S. Army Corps of Engineers, the Tennessee Valley Authority, and the U.S. Bureau of Reclamation were invited to submit assessments of water quality conditions in their own impoundments. Dams from these three agencies represent a wide range of geography, climate, and operational situations. The agencies surveyed their existing impoundments using a questionnaire developed by COE, asking field personnel what the dam-related water quality problems are and what impacts are being felt. The resulting data, although subjective and incomplete, gives a picture of the extent of known water quality problems along with an assessment of these problems on user benefits. Agency assessments based on visual observations indicate that physical water quality conditions, such as pool level fluctuations and high and low flows, may more frequently affect user benefits than poor chemical water quality conditions. For the TVA system, chemical concerns are usually more serious, even though physical parameters are more prevalent

**Figure VII-3**
**Summary of Quantitative Analyses of Large Power Dams**




NOTES:
(1) Because of missing data, the actual percentage falls somewhere within the range.
(2) Based on the population rather than the sample.
(3) Quantitative results were not representative.

concerns. It is possible that data were primarily collected at projects where problems are known or suspected, thereby introducing a pessimistic bias.

The COE operates more than 700 impoundments and has collected questionnaires on 470. A sample of 46 (10 percent) was selected based on project type and COE District. Data were available for approximately 50 to 60 percent of the projects sampled. Approximately 35 to 40 percent of sampled projects with data had problematic conditions in the tailwaters. Most prevalent were flow fluctuations and high and low flow issues, low dissolved oxygen, and erosion and transport of sediment. Problematic conditions in impoundment pools were identified in 40 to 50 percent of the sampled projects with data. Most prevalent were eutrophication problems (high nutrients, low dissolved oxygen, algal blooms, and macrophytes). Additional conditions of concern in pools were excessive concentrations of reduced iron and manganese in bottom waters and accumulation of sediment and contaminants.

TVA assessed all 33 of their large projects, including all of their hydropower projects and four nonhydro projects. Small impoundments were not assessed. Data were available for dissolved oxygen, temperature, flow, pool levels, and macrophytes at all projects. Data for the other parameters were available for an average of 60 percent of the projects. Water uses were severely impacted at several sites. In reservoir pools, the most significant impacts were pool level fluctuations (50 percent of the projects with data), bacteria (30 percent), and turbidity, algae, macrophytes, sediment accretion, and shore erosion (all at 15 to 20 percent). Tailwaters primarily experienced significant problems with low dissolved oxygen, flow (high, low, and fluctuating), and low temperature, occurring at 15 to 20 percent of the projects with data.

USBR maintains 349 impoundments in the 17 western states; of these, 250 (72 percent) responded to the questionnaires. In approximately 54 percent of the reservoir pools and 59 percent of the tailwater cases, no data were available. The main impact-producing conditions identified at USBR reservoirs are drawdown and pool fluctuation, which are associated with a mode of operation that combines rapid spring filling of reservoirs with a steady withdrawal of water to satisfy irrigation, municipal, and industrial demands during the long dry season. These two conditions were rated as having at least significant impacts on user benefits in 36 percent and 35 percent, respectively, of the reservoirs with available data. High flow was the main impact-producing condition noted in USBR tailwaters, probably reflecting the high spring inflows and spillway discharges of the mid-1980's. This condition was rated as having a significant impact on user benefits in 21 percent of the rated tailwaters. The next two significant impact-producing conditions cited were low flow and taste and odor problems, each with a cumulative rating of at least significant in about 13 percent of the tailwaters with available data.

## SUMMARY OF EPA ANALYSES AND AGENCY ASSESSMENTS

The results of the four EPA analyses conducted for this study (mixing, tailwater dissolved oxygen, upstream/downstream comparison of parameters, and phosphorous enrichment) cannot be directly related to the findings of the Agency assessments due to differences in the analytical methods and parameters. However, a few simple comparisons can be made which illustrate the likely range in which certain dam water quality conditions occur. The study assessment of large power impoundments found that low dissolved oxygen in tailwaters occurs more frequently in summer than winter and at large power impoundments over small power impoundments. The COE reported that approximately 33 percent of the projects assessed had dissolved oxygen concentrations below saturation during the summer months, while TVA reported seasonal low dissolved oxygen in 70 percent of their reservoir hypolimnia or bottom waters. USBR experienced at least intermittent low dissolved oxygen levels in only 9 percent of their reservoirs.

The upstream/downstream comparison found low dissolved oxygen in 23 to 50 percent of large power impoundment tailwaters. Assessments by the COE and TVA reported similar results, although their data were not restricted to large power impoundments. COE reported 20 percent of their project tailwaters experienced at least intermittent problems with low dissolved oxygen, while TVA reported 38 percent with at least intermittent problems. USBR reported only 4 percent of their projects as experiencing at least intermittent problems with low dissolved oxygen in tailwaters. Both the data analyzed by this study and the information provided by the Agencies indicate that low dissolved oxygen is influenced, in part, by climate and is therefore more likely to occur in eastern dams, and particularly in southeastern dams.

The phosphorous analysis estimated phosphorous enrichment within impoundment pools of large power dams as a potential indicator of eutrophication. The analysis showed 58 to 78 percent of the large power dam pools had phosphorous above a guidance value of 0.025 mg/l. The Agency assessments subjectively estimated the frequency of occurrence of high nutrient loads (presumably a combination of nitrogen and phosphorous) in pools. Agency impoundments were not restricted to large power dams. High nutrient loads were reported in 35 percent of the COE's pools, 30 percent of TVA's pools, and 15 percent of USBR's pools.

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* All references with an asterisk have been cited within the body of the report and appendices.

## APPENDIX B
## SAMPLE/CASE STUDY DATA BASE

This section contains a compilation of the various data reflected in the 120 sample and 15 case study facilities. The 135 dams have been broken into four tables. Each table reflects a category of facility; large power dams, large nonpower dams, small dams, and case study dams. Every page of the tables contains the category (i.e., random sample or case study), the COE National Inventory of Dam identification number, and the name of the facility. Although these tables include a significant amount of the data and statistics used in the report, the individual STORET monitoring data are excluded.

The sample tables consist of three pages for each partition. The first page contains physical information taken from the COE National Inventory: the location, power rating of the hydroelectric installation (if any), normal volume, hydraulic dam height, and maximum spillway capacity. Morphologic data, including estimates based on the regression analysis discussed in the body of the report, are also included. These data include area, annual inflow, and length of the reservoir. Note that where data were obtained from other sources, (i.e., EPA IHS flow file, agencies, or by direct measurement from USGS topographical maps), they replace the calculated estimates. This is done throughout the tables. Finally, the first page of the tables provides the calculated Froude and Phosphorus Retention Coefficient values.

The second page of the sample tables contains information relevant to the phosphorus and eutrophication analyses discussed in the body of the report. Data used in the application of the Vollenweider model are checked. The upstream phosphorus, inpool phosphorus, and downstream phosphorus data are averages based on the tabulated sample size. The in-pool phosphorus estimate is based on the actual data, a Vollenweider estimate, or usage of the downstream level as the best estimate. Also shown on this page of the table is the probability of noncompliance statistics for summer and winter for the appropriate stations.

The third and final page of the sample tables consists of information on where, in relationship to the facilities, data for 15 water quality parameters were found. (The Case Studies category does not have this information.) The data were categorized by being upstream (**U**), in-pool (**P**), or downstream (**D**). The table reflects that data may have been sampled at all three locations, for example, $BOD_5$ at the Beaver Dam (AR00174), or found at none, such as TKN at the Cooper Dam (AK00001). Notice that the location of the phosphorus information on the second page of the tables are reflected under the column **PHOS** on page three.

The case study table consists of one page and combines information similar to that on the first page of the sample tables with the noncompliance data from the second page described above.

| RANDOM SAMPLE | DAM ID | NAME | LAT/LONG D | LAT/LONG M | LAT/LONG D | LAT/LONG M | POWER (100KW) | V (ac-ft) | H (ft) | QMAX (cfs) | Qave (cfs) DATA | Qave (cfs) ESTIMATE | AREA (acres) DATA | AREA (acres) ESTIMATE | LENGTH (feet) DATA | LENGTH (feet) ESTIMATE | FROUDE | RETENTION COEFF. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L-P | AK00001 | COOPER DAM | 60 | 26 | 149 | 50 | 15 | 230000 | 50 | 1700 | | 110 | 1980 | 1980 | 30600 | 30600 | 0.001 | 0.551 |
| | AL01416 | H NEELY HENRY | 33 | 47 | 86 | 3 | 729 | 109000 | 57 | 310700 | 10827 | 10827 | | 5512 | | 60351 | 2.228 | 0.977 |
| | AL01418 | LAY DAM | 32 | 58 | 86 | 31 | 1770 | 265000 | 103 | 417000 | 15049 | 15049 | 7040 | 7040 | 95000 | 95000 | 1.053 | 0.979 |
| | AR00174 | BEAVER DAM | 36 | 25 | 93 | 51 | 1120 | 1652000 | 218 | 342000 | 1601 | 1601 | 40960 | 40960 | 258700 | 258700 | 0.046 | 0.463 |
| | AR00534 | CARPENTER | 34 | 27 | 93 | 2 | 560 | 19000 | 110 | 184000 | 2348 | 2348 | | 498 | | 18138 | 0.432 | 0.990 |
| | AZ10309 | DAVIS | 35 | 12 | 114 | 34 | 225 | 1577000 | 135 | 214000 | 121134 | 121134 | | 33671 | | 149162 | 1.798 | 0.988 |
| | AZ10317 | THEODORE ROOSEVELT | 33 | 40 | 111 | 10 | 400 | 138200 | 234 | 150000 | 965 | 965 | 15000 | 15000 | 59700 | 59700 | 0.333 | 0.587 |
| | CA00042 | THERMALITO AFTERBAY | 39 | 27 | 121 | 38 | 1151 | 57000 | 33 | | 4775 | 4775 | | 4979 | | 57358 | 3.085 | 0.955 |
| | CA00240 | NEW EXCHEQUER 58-002 | 37 | 35 | 120 | 16 | 800 | 1026000 | 437 | 350000 | 1312 | 1312 | 5000 | 5000 | 78700 | 78700 | 0.004 | 0.853 |
| | CA00382 | SALT SPRINGS 97-066 | 38 | 30 | 120 | 13 | 94 | 139400 | 302 | 55800 | 210 | 210 | | 1330 | | 29651 | 0.003 | 0.777 |
| | CA00390 | RELIEF 97-080 | 38 | 17 | 119 | 44 | 82 | 15122 | 132 | 4400 | | 285 | | 330 | | 14772 | 0.045 | 0.950 |
| | CO01658 | GREEN MOUNTAIN | 39 | 53 | 106 | 20 | 216 | 154600 | 258 | 25000 | 553 | 553 | 2120 | 2120 | 29500 | 29500 | 0.011 | 0.852 |
| | FL00642 | MANATEE COOLING WATER RES. | 27 | 37 | 82 | 20 | 1724 | 23000 | 71 | 1965 | 71 | 71 | | 934 | | 24840 | 0.023 | 0.627 |
| | GA00826 | GOAT ROCK | 32 | 37 | 85 | 5 | 260 | 11000 | 68 | 200000 | 6586 | 6586 | | 466 | | 17553 | 3.274 | 0.997 |
| | GA03742 | ALLATOONA LAKE DAM PWRHSE | 34 | 10 | 84 | 44 | 740 | 367470 | 170 | 321000 | 1927 | 1927 | 17440 | 17440 | 100320 | 100320 | 0.184 | 0.709 |
| | IA00007 | MISSISSIPPI R LOCKS+DAM #15 | 41 | 31 | 90 | 34 | 3 | 30000 | 32 | 306700 | 47881 | 47881 | | 2702 | | 42257 | 44.651 | 0.997 |
| | ID00223 | MILNER | 42 | 31 | 114 | 1 | 1188 | 14200 | 73 | 103000 | | 6666 | | 561 | | 19248 | 2.622 | 0.996 |
| | KY03048 | KENTUCKY | 37 | 1 | 88 | 16 | 175 | 2121000 | 190 | 1200000 | 31855 | 31855 | | 32177 | | 145816 | 0.244 | 0.956 |
| | ME00143 | MATTASEUNK DAM | 45 | 34 | 68 | 25 | 19 | 26076 | 41 | 58000 | 5845 | 5845 | | 1833 | | 34805 | 4.031 | 0.986 |
| | MI00151 | ALLEGAN | 42 | 35 | 85 | 58 | 26 | 12000 | 33 | 18300 | 1286 | 1286 | 1300 | 1300 | 30000 | 30000 | 2.560 | 0.956 |
| | MI00161 | COOKE | 44 | 28 | 83 | 34 | 90 | 36700 | 48 | 15500 | 1577 | 1577 | | 2204 | | 38161 | 0.724 | 0.940 |
| | MI00186 | MIO | 44 | 40 | 84 | 8 | 50 | 13900 | 38 | 4900 | 1528 | 1528 | 1920 | 1920 | 19500 | 19500 | 2.176 | 0.946 |
| | MI00550 | SANFORD DAM | 43 | 41 | 84 | 23 | 42 | 26200 | 32 | 29000 | 750 | 750 | 2300 | 2300 | 44000 | 44000 | 0.813 | 0.878 |
| | MN00653 | RAINY LAKE | 48 | 36 | 93 | 24 | 12 | 3312000 | 34 | 47900 | 1460 | 1460 | | 280780 | | 430741 | 0.118 | 0.103 |
| | MO30200 | STOCTON DAM | 37 | 42 | 93 | 46 | 520 | 892000 | 123 | 174000 | 972 | 972 | 27900 | 27900 | 113000 | 113000 | 0.028 | 0.435 |
| | MT00224 | THOMPSON FALLS | 47 | 35 | 115 | 21 | 300 | 14970 | 50 | 230000 | 20828 | 20828 | | 863 | | 23880 | 14.078 | 0.998 |
| | NC00338 | THORPE NUMBER 1 DAM | 35 | 12 | 83 | 9 | 210 | 59000 | 140 | 49500 | 83 | 83 | | 1215 | | 28332 | 0.006 | 0.601 |
| | NC00549 | NARROUS DAM | 35 | 25 | 80 | 6 | 965 | 378992 | 196 | 324000 | 5445 | 5445 | 7510 | 7510 | 38000 | 38000 | 0.080 | 0.941 |
| | NC00550 | TUCKERTOWNE LAKE DAM | 35 | 29 | 80 | 11 | 4200 | 43000 | 70 | 419000 | 5401 | 5401 | | 1771 | | 34205 | 1.300 | 0.985 |
| | NE01025 | EARTH DAM CANAL MILE 645 | 40 | 41 | 99 | 50 | 180 | 54000 | 44 | | 7 | 7 | | 3537 | | 48348 | 0.003 | 0.042 |
| | OR00002 | THE DALLES DAM | 45 | 37 | 121 | 8 | 12750 | 277000 | 114 | 2290000 | 189892 | 189892 | | 7004 | | 68030 | 8.667 | 0.998 |
| | SC00247 | SCNONAME 01007 | 34 | 16 | 82 | 37 | 28 | 16890 | 76 | | 332 | 332 | | 641 | | 20574 | 0.113 | 0.920 |
| | SC01072 | FISHING CREEK | 34 | 36 | 80 | 53 | 367 | 60000 | 90 | 532200 | 5688 | 5688 | | 1922 | | 35634 | 0.795 | 0.985 |
| | SD01094 | GAVINS POINT DAM | 42 | 51 | 97 | 29 | 100 | 375000 | 63 | 584000 | 27505 | 27505 | 25400 | 25400 | 169000 | 169000 | 6.171 | 0.960 |
| | TN03702 | OLD HICKORY DAM | 36 | 18 | 86 | 37 | 1000 | 357000 | 68 | 228000 | 18876 | 18876 | | 15133 | | 99998 | 1.647 | 0.965 |
| | TN13905 | OCOEE NUMBER 1 DAM | 35 | 6 | 84 | 39 | 180 | 54000 | 129 | 20000 | | 1294 | | 1207 | | 28237 | 0.111 | 0.959 |
| | WA00013 | BOX CANYON DAM | 48 | 47 | 117 | 25 | 600 | 100000 | 100 | 350000 | 28644 | 28644 | | 2882 | | 43643 | 2.648 | 0.995 |
| | WA00257 | ALDER DAM | 46 | 48 | 122 | 19 | 500 | 231936 | 285 | 85000 | 1441 | 1441 | 2800 | 2800 | 39372 | 39372 | 0.022 | 0.919 |
| | WI00759 | CALDRON FALLS WP186 | 45 | 21 | 88 | 14 | 64 | 15656 | 80 | 22700 | 352 | 352 | 1100 | 1100 | 18480 | 18480 | 0.215 | 0.876 |
| | WI00815 | BIRON 2WP71 | 44 | 26 | 89 | 47 | 33 | 16300 | 24 | 167100 | 4963 | 4963 | | 1958 | | 35967 | 9.667 | 0.982 |

| RANDOM SAMPLE | DAM ID | NAME | VOLLENWEIDER CORRELATION | UPSTREAM PHOSPHORUS DATA | UPSTREAM PHOSPHORUS N | IN-POOL PHOSPHORUS DATA | IN-POOL PHOSPHORUS N | IN-POOL PHOSPHORUS ESTIMATE | DOWNSTREAM PHOSPHORUS DATA | DOWNSTREAM PHOSPHORUS N | SUMMER DATA | PNC N | WINTER DATA | PNC N | TOTAL N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L-P | AK00001 | COOPER DAM | | | | 0.010 | 1 | 0.010 | | | | | | | |
| | AL01416 | H NEELY HENRY | | | | | | | | | | | | | |
| | AL01418 | LAY DAM | √ | 0.058 | 58 | 0.068 | 41 | 0.068 | | | 0.08 | 13 | - | - | 13 |
| | AR00174 | BEAVER DAM | √ | 0.055 | 4836 | 0.030 | 340 | 0.030 | 0.033 | 230 | | | | | |
| | AR00534 | CARPENTER | | | | 0.037 | 853 | 0.037 | 0.097 | 37 | | | | | |
| | AZ10309 | DAVIS | √ | 0.016 | 51 | 0.022 | 636 | 0.022 | 0.043 | 8 | | | | | |
| | AZ10317 | THEODORE ROOSEVELT | √ | 0.013 | 169 | 0.024 | 87 | 0.024 | 0.029 | 14 | | | | | |
| | CA00042 | THERMALITO AFTERBAY | | | | | | | | | | | | | |
| | CA00240 | NEW EXCHEQUER 58-002 | √ | 0.025 | 68 | 0.015 | 10 | 0.015 | 0.011 | 15 | 0.21 | 58 | 0.06 | 89 | 147 |
| | CA00382 | SALT SPRINGS 97-066 | | | | | | | | | | | | | |
| | CA00390 | RELIEF 97-080 | | | | | | | 0.036 | 38 | | | | | |
| | CO01658 | GREEN MOUNTAIN | √ | 0.037 | 110 | 0.012 | 18 | 0.012 | 0.044 | 68 | | | | | |
| | FL00642 | MANATEE COOLING WATER RES. | | 0.645 | 56 | | | 0.257 | 0.048 | 318 | 0.26 | 46 | 0.08 | 91 | 137 |
| | GA00826 | GOAT ROCK | √ | 0.069 | 190 | 0.117 | 21 | 0.117 | 0.052 | 173 | | | | | |
| | GA03742 | ALLATOONA LAKE DAM PWRHSE | √ | 0.045 | 456 | 0.085 | 410 | 0.085 | | | | | | | |
| | IA00007 | MISSISSIPPI R LOCKS+DAM #15 | | 0.224 | 107 | | | 0.142 | 0.352 | 55 | 0.00 | 17 | 0.00 | 20 | 37 |
| | ID00223 | MILNER | | 0.185 | 378 | 0.095 | 37 | 0.095 | 0.137 | 144 | 0.00 | 39 | 0.00 | 80 | 119 |
| | KY03048 | KENTUCKY | √ | 0.072 | 5 | 0.063 | 240 | 0.063 | 0.103 | 495 | 0.09 | 386 | 0.01 | 774 | 1160 |
| | ME00143 | MATTASEUNK DAM | | 0.034 | 63 | | | 0.021 | 0.146 | 6 | | | | | |
| | MI00151 | ALLEGAN | √ | 0.160 | 91 | 0.145 | 20 | 0.145 | 0.093 | 7 | 0.33 | 3 | - | - | 3 |
| | MI00161 | COOKE | | | | | | | | | | | | | |
| | MI00186 | MIO | | | | | | | | | | | | | |
| | MI00550 | SANFORD DAM | √ | 0.042 | 35 | 0.020 | 33 | 0.020 | 0.066 | 218 | 0.14 | 37 | 0.00 | 75 | 112 |
| | MN00653 | RAINY LAKE | | | | 0.039 | 89 | 0.039 | 0.067 | 960 | 0.00 | 66 | 0.00 | 112 | 178 |
| | MO30200 | STOCTON DAM | √ | 0.143 | 199 | 0.055 | 186 | 0.055 | 0.470 | 64 | 0.48 | 388 | 0.18 | 207 | 595 |
| | MT00224 | THOMPSON FALLS | | 0.020 | 51 | | | 0.013 | 0.030 | 61 | 0.00 | 8 | 0.00 | 15 | 23 |
| | NC00338 | THORPE NUMBER 1 DAM | | | | | | | | | 0.36 | 56 | 0.00 | 45 | 101 |
| | NC00549 | NARROUS DAM | √ | 0.052 | 58 | 0.055 | 187 | 0.055 | | | | | | | |
| | NC00550 | TUCKERTOWNE LAKE DAM | √ | 0.090 | 13 | 0.090 | 30 | 0.090 | 0.034 | 14 | | | | | |
| | NE01025 | EARTH DAM CANAL MILE 645 | | 0.072 | 13 | | | 0.002 | 0.057 | 13 | | | | | |
| | OR00002 | THE DALLES DAM | | 0.093 | 145 | | | 0.059 | 0.061 | 122 | 0.00 | 1 | 0.00 | 4 | 5 |
| | SC00247 | SCNONAME 01007 | | 0.150 | 151 | | | 0.088 | 0.241 | 9 | | | | | |
| | SC01072 | FISHING CREEK | √ | 0.232 | 663 | 0.163 | 44 | 0.163 | | | | | | | |
| | SD01094 | GAVINS POINT DAM | √ | 0.187 | 341 | 0.047 | 9 | 0.047 | 0.053 | 71 | | | | | |
| | TN03702 | OLD HICKORY DAM | √ | 0.187 | 1257 | 0.060 | 165 | 0.060 | 0.162 | 189 | 0.32 | 73 | 0.07 | 28 | 101 |
| | TN13905 | OCOEE NUMBER 1 DAM | | 0.047 | 222 | | | 0.029 | 0.014 | 114 | 0.01 | 376 | 0.00 | 808 | 1184 |
| | WA00013 | BOX CANYON DAM | | | | | | | | | 0.00 | 10 | 0.00 | 24 | 34 |
| | WA00257 | ALDER DAM | | 0.100 | 230 | | | 0.059 | 0.033 | 272 | 0.00 | 84 | 0.00 | 196 | 280 |
| | WI00759 | CALDRON FALLS WP186 | | | | 0.033 | 4 | 0.033 | | | | | | | |
| | WI00815 | BIRON 2WP71 | | 0.117 | 15 | | | 0.073 | 0.111 | 137 | 0.02 | 49 | 0.01 | 90 | 139 |

| RANDOM SAMPLE | DAM ID | NAME | BOD5 | CHLA | DISSO | DOWK | FEDIS | FETOT | H2S | MNDIS | MNTOT | NITTOT | NO2NO3 | PHOS | TEMP | TKN | TURB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L-P | AK00001 | COOPER DAM | - | - | P | - | P | - | - | P | - | P | P | P | P | - | - |
| | AL01416 | H NEELY HENRY | U-D | - | - | U-D | - | U | - | - | - | - | U | - | U-D | U | U |
| | AL01418 | LAY DAM | U-D | - | - | U-P-D | U | U | - | U | - | - | U-P | U-P | U-P-D | - | - |
| | AR00174 | BEAVER DAM | U-P-D | - | U | U-P-D | - | U-D | - | - | U-P-D | U-P | U-P-D | U-P-D | U-P-D | U-P-D | U-P-D |
| | AR00534 | CARPENTER | U-D | - | U | U-P-D | U | U-P | - | - | U-P | U | U-P-D | P-D | U-P-D | U-P-D | U-D |
| | AZ10309 | DAVIS | U-D | - | U-D | U-P-D | U-D | - | - | - | - | - | U-P | U-P-D | U-P-D | U-P-D | U-D |
| | AZ10317 | THEODORE ROOSEVELT | U-P-D | - | U | U-P-D | U-P | U | U-P | U-P | U | U | U-P-D | U-P-D | U-P-D | U-P-D | U-P-D |
| | CA00042 | THERMALITO AFTERBAY | D | - | - | D | D | D | - | D | - | - | - | - | D | - | - |
| | CA00240 | NEW EXCHEQUER 58-002 | U-D | - | U-D | U-P-D | U-D | U-D | - | U-D | U | U-D | U-D | U-P-D | U-P-D | U-P-D | U-D |
| | CA00382 | SALT SPRINGS 97-066 | - | - | - | D | - | P-D | - | - | P-D | - | - | - | - | - | - |
| | CA00390 | RELIEF 97-080 | D | - | - | D | D | - | - | D | - | - | - | D | D | - | - |
| | CO01658 | GREEN MOUNTAIN | U-D | - | U-D | U-P-D | U-D | U-D | - | U-D | U | U-D | U-P-D | U-P-D | U-P-D | U-P-D | U-D |
| | FL00642 | MANATEE COOLING WATER RES. | U-D | D | U-D | U-D | U-D | U-D | - | U-D | U-D | U-D | U-D | U-D | U-D | U-D | D |
| | GA00826 | GOAT ROCK | U-D | - | - | U-P-D | - | U-D | - | - | U-D | - | U-P-D | U-P-D | U-P-D | U-P | U-D |
| | GA03742 | ALLATOONA LAKE DAM PWRHSE | U-P | - | U | U-P-D | U-P | U-P-D | - | U-P | U-P-D | U-P | U-P-D | U-P | U-P-D | U-P | U |
| | IA00007 | MISSISSIPPI R LOCKS+DAM #15 | U-D | - | U | U-D | U-D | U-D | - | U | U-D | - | U-D | U-D | U-D | U | U-D |
| | ID00223 | MILNER | U-P-D | - | U-P-D | U-P-D | U-D | U-P-D | - | U | U-P-D | U-P-D | U-P-D | U-P-D | U-P-D | U-P-D | U-P-D |
| | KY03048 | KENTUCKY | U-D | - | D | U-P-D | P-D | U-P-D | - | P-D | U-P-D | P-D | P-D | U-P-D | U-P-D | P-D | U-D |
| | ME00143 | MATTASEUNK DAM | U-D | - | - | U-D | - | U | - | - | - | U | U-D | U-D | U-D | - | - |
| | MI00151 | ALLEGAN | U-D | - | D | U-P-D | U-D | - | - | U-D | D | - | U-P-D | U-P-D | U-P-D | U-D | U-D |
| | MI00161 | COOKE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | MI00186 | MIO | U | - | - | U-D | - | U-D | - | - | U-D | U-D | U-D | - | U-D | U-D | U |
| | MI00550 | SANFORD DAM | U-D | - | - | U-P-D | U-D | D | - | U | D | - | U-P-D | U-P-D | U-P-D | U-D | U |
| | MN00653 | RAINY LAKE | P-D | - | - | P-D | P | P-D | - | P | P-D | P-D | P-D | P-D | P-D | P-D | P-D |
| | MO30200 | STOCTON DAM | - | - | U-P-D | U-P-D | U-P-D | U-P-D | - | U-P-D | U-P-D | U | U-P-D | U-P-D | U-P-D | U-P-D | U-P-D |
| | MT00224 | THOMPSON FALLS | U-D | - | U-D | U-P-D | U-P-D | U-P-D | - | U-P-D | U-P-D | U-D | U-D | U-D | U-P-D | U-D | U-D |
| | NC00338 | THORPE NUMBER 1 DAM | - | - | - | U-D | - | - | - | - | - | - | - | - | - | - | - |
| | NC00549 | NARROUS DAM | U-P | - | - | U-P | - | U-P | - | - | U-P | - | U-P | U-P | U-P | - | - |
| | NC00550 | TUCKERTOWNE LAKE DAM | U | - | - | U-P | - | P | - | - | P | - | P-D | U-P-D | U-P | - | - |
| | NE01025 | EARTH DAM CANAL MILE 645 | - | - | - | - | - | - | - | - | - | - | U-D | U-D | - | - | - |
| | OR00002 | THE DALLES DAM | U-D | D | U-D | U-D | U-D | U-D | - | U-D | U-D | U-D | U-D | U-D | U-D | U-D | U-D |
| | SC00247 | SCNONAME 01007 | U-D | - | - | U-D | U-D | U-D | - | D | U-D | - | U-D | U-D | U-D | U-D | U |
| | SC01072 | FISHING CREEK | U | U | - | U-P | U | U | - | U | U | U | U-P | U-P | U-P | U-P | U |
| | SD01094 | GAVINS POINT DAM | U-D | - | U-D | U-P-D | U-D | U-D | - | U-D | U-D | U-D | U-P-D | U-P-D | U-P-D | U-P-D | U-D |
| | TN03702 | OLD HICKORY DAM | U-D | - | - | U-P-D | U-P-D | U-P-D | - | U-P-D | U-P-D | P-D | U-P-D | U-P-D | U-P-D | U-P-D | U |
| | TN13905 | OCOEE NUMBER 1 DAM | U-D | - | U-D | U-D | U-D | U-D | - | U-D | U-D | U | U-D | U-D | U-D | U-D | U-D |
| | WA00013 | BOX CANYON DAM | - | - | U-D | U-D | D | D | - | - | - | - | - | - | U-D | - | U-D |
| | WA00257 | ALDER DAM | - | - | - | U-P-D | P | - | - | P | - | U-D | U-D | U-D | U-P-D | U-D | U-D |
| | WI00759 | CALDRON FALLS WP186 | - | - | - | U-P | - | - | - | - | - | U | U | P | - | - | - |
| | WI00815 | BIRON 2WP71 | U-D | - | U | U-D | U | - | - | U | U | U | U | U-D | U-D | - | - |

| RANDOM SAMPLE | DAM ID | NAME | LAT/LONG D | LAT/LONG M | LAT/LONG D | LAT/LONG M | POWER (100KW) | V (ac-ft) | H (ft) | QMAX (cfs) | Qave (cfs) DATA | Qave (cfs) ESTIMATE | AREA (acres) DATA | AREA (acres) ESTIMATE | LENGTH (feet) DATA | LENGTH (feet) ESTIMATE | FROUDE | RETENTION COEFF. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L-NP | AL00017 | BIG CREEK LAKE | 30 | 43 | 88 | 21 | | 105000 | 56 | 35000 | 262 | 262 | | 5405 | | 59760 | 0.056 | 0.517 |
| | AZ10302 | RED LAKE DAM | 35 | 55 | 109 | 2 | | 15517 | 22 | 420 | 11 | 11 | | 2033 | | 36652 | 0.025 | 0.107 |
| | CA00029 | WHALE ROCK RESERVOIR | 35 | 27 | 120 | 53 | | 40000 | 176 | 3120 | 46 | 46 | | 655 | | 20806 | 0.003 | 0.608 |
| | CA00453 | GEM LAKE 104-037 | 37 | 45 | 119 | 9 | | 17604 | 70 | 1080 | | 70 | | 725 | | 21886 | 0.026 | 0.680 |
| | CA00458 | INDEPENDENCE 105-006 | 39 | 27 | 120 | 17 | | 18500 | 24 | 660 | 24 | 24 | 5760 | 5760 | 13200 | 13200 | 0.039 | 0.084 |
| | CA00516 | LAKE LEAVITT 236-002 | 40 | 23 | 120 | 30 | | 14000 | 14 | 330 | 158 | 158 | 938 | 938 | 8202 | 8202 | 0.046 | 0.788 |
| | CA00813 | SAN ANTONIO | 35 | 48 | 120 | 53 | | 348000 | 179 | 35100 | 47 | 47 | 6400 | 6400 | 60700 | 60700 | 0.001 | 0.139 |
| | CA01107 | INDIAN VALLEY 1080-002 | 39 | 5 | 122 | 32 | | 300000 | 203 | 36000 | 75 | 75 | | 4260 | | 53055 | 0.001 | 0.280 |
| | CA10142 | CLEAR LAKE RESERVIOR | 41 | 48 | 121 | 10 | | 388500 | 8 | | | | | 139977 | | 304131 | | |
| | CA10162 | LAKE TAHOE | 39 | 10 | 120 | 9 | | 732000 | 10 | 2500 | 340 | 340 | | 210992 | | 373393 | 0.367 | 0.034 |
| | CO00213 | BARKER MEADOW DAM | 39 | 38 | 105 | 28 | | 11500 | 173 | 6719 | 63 | 63 | | 192 | | 11252 | 0.008 | 0.879 |
| | CO00384 | NORTH STERLING | 40 | 47 | 103 | 16 | | 80588 | 86 | 12093 | 453 | 453 | | 2701 | | 42247 | 0.059 | 0.787 |
| | FL00294 | CULVERT #9 | 27 | 12 | 80 | 46 | | 4596000 | 18 | | | | | 735974 | | 697371 | | |
| | FL00315 | LAKE OKEECHOBEE | 26 | 57 | 80 | 37 | | 4596000 | 18 | | | | | 735974 | | 697371 | | |
| | FL00335 | STRUCTURE NUMBER 10D | 26 | 23 | 80 | 23 | | 300000 | 9 | 14800 | | 958 | | 96080 | | 251971 | 1.894 | 0.180 |
| | FL00358 | STRUCTURE NUMBER 38 | 26 | 14 | 80 | 18 | | 368000 | 16 | | | | | 66295 | | 209302 | | |
| | FL00369 | STRUCTURE NUMBER 12C | 25 | 46 | 80 | 44 | | 840000 | 13 | 8000 | | 518 | | 186248 | | 350815 | 0.352 | 0.058 |
| | GA02364 | LAKE ARROWHEAD | 34 | 17 | 84 | 36 | | 16223 | 107 | 28509 | | 1845 | | 437 | | 16994 | 0.383 | 0.989 |
| | IL00334 | EAST FORK LAKE DAM | 38 | 46 | 88 | 4 | | 12460 | 84 | 20061 | 231 | 231 | 990 | 990 | 18000 | 18000 | 0.195 | 0.837 |
| | IN03004 | MISSISSINEWA LAKE DAM | 40 | 43 | 85 | 58 | | 75184 | 137 | 122400 | 515 | 515 | 3570 | 3570 | 70900 | 70900 | 0.169 | 0.761 |
| | KY00275 | CANNON CREEK DAM | 36 | 41 | 83 | 42 | | 11300 | 125 | 3200 | 141 | 141 | | 261 | | 13122 | 0.028 | 0.923 |
| | KY03055 | CAVE RUN LAKE DAM | 38 | 8 | 83 | 32 | | 222581 | 139 | 158000 | 1081 | 1081 | 7040 | 7040 | 95000 | 95000 | 0.107 | 0.772 |
| | LA00285 | MILLERS LAKE DAM | 30 | 44 | 92 | 22 | | 10000 | 6 | 48 | 36 | 36 | 5860 | 5860 | 11483 | 11483 | 0.178 | 0.119 |
| | ME00101 | WILSON POND DAM | 44 | 17 | 70 | 2 | | 10280 | 14 | 540 | 12 | 12 | 589 | 589 | 19500 | 19500 | 0.010 | 0.310 |
| | ME00424 | ABBOTT BROOK DIKE | 46 | 8 | 69 | 36 | | 10500 | 11 | 1600 | | 104 | | 2751 | | 42639 | 0.810 | 0.454 |
| | ME06212 | LOON LAKE DAM | 44 | 58 | 70 | 1 | | 202000 | 24 | 0 | 6 | 6 | 4430 | 4430 | 18850 | 18850 | 0.000 | 0.029 |
| | MI00176 | HUBBARD LAKE DAM | 44 | 52 | 83 | 36 | | 34200 | 8 | 1100 | 120 | 120 | 8260 | 8260 | 38400 | 38400 | 0.239 | 0.243 |
| | MN00246 | WAUKENABO LAKE | 46 | 44 | 93 | 38 | | 11174 | 7 | 560 | 28 | 28 | 560 | 560 | 4752 | 4752 | 0.004 | 0.525 |
| | MN00770 | WHITE WATER RESERVOIR DAM | 47 | 29 | 92 | 11 | | 20562 | 35 | | | | | 1693 | | 33451 | | |
| | MN00771 | WHITE WATER RESERVOIR DAM | 47 | 31 | 92 | 12 | | 20562 | 31 | | | | | 1912 | | 35544 | | |
| | MO20729 | STERITT CREEK DIKE | 38 | 17 | 93 | 22 | | 1202200 | 55 | | | | | 63004 | | 204041 | | |
| | NJ00332 | UPPER RESERVIOR DAM 1 | 40 | 59 | 74 | 34 | | 15718 | 38 | | | | | 1192 | | 28068 | | |
| | OH00928 | CAESAR CREEK LAKE DIKE "A" | 39 | 28 | 83 | 58 | | 102000 | 63 | 91400 | 262 | 262 | 2796 | 2796 | 39600 | 39600 | 0.020 | 0.674 |
| | OK11039 | SHAWNEE CITY LAKE NUMBER 1 | 35 | 21 | 97 | 4 | | 22600 | 55 | 31000 | 0 | 0 | | 1184 | | 27976 | 0.000 | 0.000 |
| | PA00107 | MAHONING CREEK DAM | 40 | 55 | 79 | 17 | | 31280 | 162 | 120000 | 612 | 612 | | 557 | | 19177 | 0.049 | 0.960 |
| | PA00924 | BLUE MARSH DIKE | 40 | 22 | 76 | 2 | | 22900 | 22 | 74800 | 318 | 318 | 1500 | 1500 | 40000 | 40000 | 0.267 | 0.824 |
| | UT10128 | MOON LAKE | 40 | 34 | 110 | 29 | | 49500 | 75 | 10000 | 114 | 114 | 580 | 580 | 16000 | 16000 | 0.003 | 0.813 |
| | UT10130 | NORTH BOTTLE HOLLOW | 40 | 17 | 109 | 52 | | 11100 | 53 | | 327 | 327 | | 604 | | 19973 | 0.235 | 0.923 |
| | WI00764 | BURNT ROLLWAYS 1909C361 | 45 | 54 | 89 | 9 | | 18000 | 9 | 2700 | | 175 | | 5765 | | 61720 | 1.410 | 0.401 |
| | WV06108 | OPEKISKA LOCK AND DAM | 39 | 34 | 80 | 3 | | 14400 | 36 | 117000 | 4254 | 4254 | | 1153 | | 27602 | 4.799 | 0.988 |

| RANDOM SAMPLE | DAM ID | NAME | VOLLENWEIDER CORRELATION | UPSTREAM PHOSPHORUS DATA | UPSTREAM PHOSPHORUS N | IN-POOL PHOSPHORUS DATA | IN-POOL PHOSPHORUS N | IN-POOL PHOSPHORUS ESTIMATE | DOWNSTREAM PHOSPHORUS DATA | DOWNSTREAM PHOSPHORUS N | SUMMER DATA | PNC N | WINTER DATA | PNC N | TOTAL N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L-NP | AL00017 | BIG CREEK LAKE | | | | | | | | | | | | | |
| | AZ10302 | RED LAKE DAM | | | | | | | | | | | | | |
| | CA00029 | WHALE ROCK RESERVOIR | | | | | | | | | | | | | |
| | CA00453 | GEM LAKE 104-037 | | | | | | | | | | | | | |
| | CA00458 | INDEPENDENCE 105-006 | | | | | | | 0.014 | 5 | 0.00 | 1 | 0.00 | 3 | 4 |
| | CA00516 | LAKE LEAVITT 236-002 | | | | | | | | | | | | | |
| | CA00813 | SAN ANTONIO | | 0.162 | 9 | 0.225 | | 0.225 | 0.195 | 12 | 0.00 | 8 | 0.00 | 16 | 24 |
| | CA01107 | INDIAN VALLEY 1080-002 | | 0.071 | 67 | | | 0.013 | 0.060 | 125 | 0.46 | 50 | 0.18 | 61 | 111 |
| | CA10142 | CLEAR LAKE RESERVIOR | | | | | | | | | | | | | |
| | CA10162 | LAKE TAHOE | | 0.088 | 1832 | 0.008 | 483 | 0.008 | 0.018 | 76 | 0.00 | 22 | 0.00 | 44 | 66 |
| | CO00213 | BARKER MEADOW DAM | √ | 0.015 | 29 | 0.026 | 26 | 0.026 | | | | | | | |
| | CO00384 | NORTH STERLING | | | | | | | | | 0.07 | 15 | - | - | 15 |
| | FL00294 | CULVERT #9 | | | | | | | | | | | | | |
| | FL00315 | LAKE OKEECHOBEE | | | | | | | | | | | | | |
| | FL00335 | STRUCTURE NUMBER 10D | | | | | | | | | | | | | |
| | FL00358 | STRUCTURE NUMBER 38 | | | | | | | | | | | | | |
| | FL00369 | STRUCTURE NUMBER 12C | | | | | | | | | | | | | |
| | GA02364 | LAKE ARROWHEAD | | | | | | | | | | | | | |
| | IL00334 | EAST FORK LAKE DAM | | | | 0.026 | 24 | 0.026 | | | | | | | |
| | IN03004 | MISSISSINEWA LAKE DAM | √ | 0.373 | 510 | 0.187 | 33 | 0.187 | 0.134 | 231 | 0.02 | 43 | 0.00 | 42 | 85 |
| | KY00275 | CANNON CREEK DAM | | 0.605 | 2 | | | 0.356 | | | | | | | |
| | KY03055 | CAVE RUN LAKE DAM | | 0.050 | 1 | 0.024 | 313 | 0.024 | 0.027 | 68 | 0.00 | 38 | 0.00 | 48 | 86 |
| | LA00285 | MILLERS LAKE DAM | | | | | | | | | | | | | |
| | ME00101 | WILSON POND DAM | | | | | | | | | | | | | |
| | ME00424 | ABBOTT BROOK DIKE | | | | | | | | | | | | | |
| | ME06212 | LOON LAKE DAM | | | | | | | | | | | | | |
| | MI00176 | HUBBARD LAKE DAM | | | | 0.013 | 8 | 0.013 | | | | | | | |
| | MN00246 | WAUKENABO LAKE | | | | 0.050 | 1 | 0.050 | | | | | | | |
| | MN00770 | WHITE WATER RESERVOIR DAM | | | | 0.065 | 27 | 0.065 | | | | | | | |
| | MN00771 | WHITE WATER RESERVOIR DAM | | | | | | | | | | | | | |
| | MO20729 | STERITT CREEK DIKE | | | | | | | | | | | | | |
| | NJ00332 | UPPER RESERVIOR DAM 1 | | | | | | | | | | | | | |
| | OH00928 | CAESAR CREEK LAKE DIKE "A" | √ | 0.148 | 413 | 0.083 | 67 | 0.083 | 0.126 | 82 | | | | | |
| | OK11039 | SHAWNEE CITY LAKE NUMBER 1 | | | | | | | | | | | | | |
| | PA00107 | MAHONING CREEK DAM | | | | 0.018 | 61 | 0.018 | 0.103 | 188 | 0.00 | 46 | 0.01 | 84 | 130 |
| | PA00924 | BLUE MARSH DIKE | √ | 0.197 | 276 | 0.074 | 95 | 0.074 | 0.344 | 252 | 0.00 | 44 | 0.01 | 81 | 125 |
| | UT10128 | MOON LAKE | √ | 0.017 | 28 | 0.010 | 25 | 0.010 | 0.010 | 1 | | | | | |
| | UT10130 | NORTH BOTTLE HOLLOW | | | | | | | | | | | | | |
| | WI00764 | BURNT ROLLWAYS 1909C361 | | | | | | | | | | | | | |
| | WV06108 | OPEKISKA LOCK AND DAM | | 0.018 | 10 | | | 0.011 | 0.068 | 239 | 0.08 | 39 | 0.00 | 24 | 63 |

| RANDOM SAMPLE | DAM ID | NAME | BOD5 | CHLA | DISSO | DOWK | FEDIS | FETOT | H2S | MNDIS | MNTOT | NITTOT | NO2NO3 | PHOS | TEMP | TKN | TURB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L-NP | AL00017 | BIG CREEK LAKE | - | - | P | - | - | P | - | P | - | - | - | - | - | - | - |
| | AZ10302 | RED LAKE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | CA00029 | WHALE ROCK RESERVOIR | - | - | - | - | - | P | - | - | - | - | - | - | - | - | - |
| | CA00453 | GEM LAKE 104-037 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | CA00458 | INDEPENDENCE 105-006 | - | - | - | D | - | D | - | - | - | - | - | D | D | - | - |
| | CA00516 | LAKE LEAVITT 236-002 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | CA00813 | SAN ANTONIO | U-D | - | P | U-P-D | U-P | - | - | - | - | P | P | U-P-D | U-P-D | - | - |
| | CA01107 | INDIAN VALLEY 1080-002 | - | - | - | U-D | D | D | - | D | D | - | - | U-D | U-D | - | - |
| | CA10142 | CLEAR LAKE RESERVIOR | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | CA10162 | LAKE TAHOE | - | - | U-D | U-P-D | U-D | U-P-D | - | U-D | U-P | U-P-D | U-P-D | U-P-D | U-P-D | U-P-D | U-P-D |
| | CO00213 | BARKER MEADOW DAM | - | - | U | P | U | - | - | U | - | - | U-P | U-P | U-P-D | - | - |
| | CO00384 | NORTH STERLING | - | - | P-D | P-D | P-D | - | - | P-D | - | - | - | - | - | - | - |
| | FL00294 | CULVERT #9 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | FL00315 | LAKE OKEECHOBEE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | FL00335 | STRUCTURE NUMBER 10D | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | FL00358 | STRUCTURE NUMBER 38 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | FL00369 | STRUCTURE NUMBER 12C | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | GA02364 | LAKE ARROWHEAD | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | IL00334 | EAST FORK LAKE DAM | - | - | - | P | - | P | - | - | P | - | P | P | P | - | - |
| | IN03004 | MISSISSINEWA LAKE DAM | U-P-D | - | - | U-P-D | U-P-D | U-P-D | - | U-P-D | U-P-D | - | U-P-D | U-P-D | U-P-D | U-P-D | U-D |
| | KY00275 | CANNON CREEK DAM | - | - | U | - | U | U | - | U | U | - | U | U | - | - | - |
| | KY03055 | CAVE RUN LAKE DAM | P-D | - | D | P-D | P-D | P-D | - | P-D | P-D | - | U-P | U-P-D | P-D | U-P-D | U |
| | LA00285 | MILLERS LAKE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | ME00101 | WILSON POND DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | ME00424 | ABBOTT BROOK DIKE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | ME06212 | LOON LAKE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | MI00176 | HUBBARD LAKE DAM | - | - | P | U-P | - | U-P | - | - | U | U | U-P | P | - | - | - |
| | MN00246 | WAUKENABO LAKE | - | - | - | P | - | - | - | - | - | - | - | P | P | - | - |
| | MN00770 | WHITE WATER RESERVOIR DAM | - | - | - | P | - | - | - | - | - | - | P | P | P | - | - |
| | MN00771 | WHITE WATER RESERVOIR DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | MO20729 | STERITT CREEK DIKE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | NJ00332 | UPPER RESERVIOR DAM 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | OH00928 | CAESAR CREEK LAKE DIKE "A" | U-P-D | - | U | U-P-D | U-P-D | U-P-D | - | U-P-D | U-P-D | U-D | U-P-D | U-P-D | U-P-D | U-P-D | U-D |
| | OK11039 | SHAWNEE CITY LAKE NUMBER 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | PA00107 | MAHONING CREEK DAM | D | - | - | U-P-D | D | U-P-D | - | D | U-P-D | - | P-D | P-D | U-P-D | P-D | D |
| | PA00924 | BLUE MARSH DIKE | U-D | - | - | U-P-D | U-P | U-D | - | U-P | U-D | U-P | U-P | U-P-D | U-P-D | U-P-D | U-D |
| | UT10128 | MOON LAKE | - | - | U-D | U-P-D | - | U | - | - | U-P-D | - | U-P | U-P-D | U-P-D | - | - |
| | UT10130 | NORTH BOTTLE HOLLOW | D | - | - | - | D | D | - | D | D | - | - | - | - | - | D |
| | WI00764 | BURNT ROLLWAYS 1909C361 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | WV06108 | OPEKISKA LOCK AND DAM | U-D | - | D | U-D | U-D | U-D | - | U-D | U-D | - | U-D | U-D | U-D | U-D | U-D |

| RANDOM SAMPLE | DAM ID | NAME | LAT/LONG D | M | D | M | POWER (100KW) | V (ac-ft) | H (ft) | QMAX (cfs) | Qave (cfs) DATA | ESTIMATE | AREA (acres) DATA | ESTIMATE | LENGTH (feet) DATA | ESTIMATE | FROUDE | RETENTION COEFF. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SMALL | AR00419 | CANEY CREEK SITE 2 DAM | 35 | 16 | 90 | 46 | | 150 | 21 | | | | | 21 | | 3688 | | |
| | CO00612 | PEDRO | 39 | 2 | 107 | 55 | | 180 | 23 | 400 | | 26 | | 23 | | 3861 | 0.511 | 0.962 |
| | CT00646 | PARIZEK POND DAM | 41 | 53 | 72 | 17 | | 56 | 12 | 30 | | 2 | | 13 | | 2981 | 0.182 | 0.761 |
| | GA03560 | WALKER LAKE DAM | 31 | 44 | 83 | 21 | | 33 | 10 | 410 | | 27 | | 10 | | 2507 | 4.271 | 0.984 |
| | IA00765 | SITE 10-2 MCCALL SWSHED ST6 | 42 | 6 | 95 | 57 | | 46 | 36 | 158 | | 10 | | 4 | | 1560 | 0.204 | 0.984 |
| | IA01540 | LEDGEWOOD CREEK WTRSHD SITE | 40 | 38 | 95 | 30 | | 43 | 44 | | | | | 3 | | 1364 | | |
| | IA01731 | 6-5495 LUM HOLLOW SUBWTRSHD | 42 | 16 | 96 | 1 | | 10 | 43 | | | | | 1 | | 666 | | |
| | IL01221 | MSDGC DAM NO. 9 (1975 RPRT) | 40 | 30 | 90 | 9 | | 56 | 26 | 105 | | 7 | | 6 | | 2025 | 0.200 | 0.960 |
| | IN00711 | RALPH KETCHUM LAKE DAM | 39 | 18 | 86 | 47 | | 55 | 23 | 195 | | 13 | | 7 | | 2134 | 0.451 | 0.976 |
| | KS00412 | KSNONAME 412 | 39 | 19 | 97 | 31 | | 15 | 15 | 820 | | 53 | | 3 | | 1380 | 6.896 | 0.998 |
| | KS01335 | KSNONAME1335 | 38 | 27 | 96 | 21 | | 42 | 15 | 636 | 0 | 0 | | 8 | | 2309 | 0.000 | 0.000 |
| | KS01513 | KSNONAME 1513 | 39 | 44 | 95 | 53 | | 10 | 25 | 542 | | 35 | | 1 | | 873 | 2.595 | 0.999 |
| | KS01702 | KSNONAME 1702 | 38 | 20 | 99 | 7 | | 50 | 23 | 452 | | 29 | | 6 | | 2035 | 1.097 | 0.990 |
| | KS03372 | KSNONAME 3372 | 39 | 40 | 99 | 40 | | 64 | 19 | | | | | 10 | | 2533 | | |
| | KS04982 | KSNONAME 4982 | 38 | 5 | 100 | 17 | | 50 | 21 | | | | | 7 | | 2130 | | |
| | KS04993 | KSNONAME 4993 | 38 | 3 | 101 | 20 | | 30 | 13 | | | | | 7 | | 2097 | | |
| | KY00271 | TYNER LAKE DAM | 37 | 23 | 83 | 55 | | 2365 | 67 | 3207 | | 208 | | 102 | | 8200 | 0.228 | 0.978 |
| | KY00642 | WALLACE AND BOWLING LK DAM | 38 | 3 | 85 | 27 | | 43 | 27 | 503 | | 33 | | 5 | | 1742 | 1.035 | 0.994 |
| | MA00967 | HODGES VILLAGE | 42 | 7 | 71 | 53 | | 0 | 50 | 25800 | | 1670 | | | | | | 1.000 |
| | MI01262 | SANITATION DAM | 42 | 31 | 84 | 39 | | 8 | 2 | | 484 | 484 | | 12 | | 2760 | 1768.92 | 0.999 |
| | MO30855 | AUTUMN LAKE DAM | 38 | 12 | 92 | 43 | | 42 | 25 | 0 | | 0 | | 5 | | 1789 | 0.000 | 0.000 |
| | MT01323 | OLSEN #1 | 48 | 32 | 108 | 4 | | 18 | 20 | | 2 | 2 | | 3 | | 1309 | 0.15 | 0.945 |
| | MT01674 | POWELL #2 | 46 | 3 | 105 | 52 | | 29 | 17 | | | | | 5 | | 1803 | | |
| | NC00382 | DUPONT DAM | 35 | 11 | 82 | 37 | | 130 | 23 | 99 | 185 | 185 | | 16 | | 3281 | 4.301 | 0.996 |
| | NE01654 | FRAHM DAM | 40 | 11 | 98 | 1 | | 27 | 16 | 185 | | 12 | | 5 | | 1793 | 1.053 | 0.982 |
| | NY00169 | MARIAVILLE LAKE DAM | 42 | 50 | 74 | 8 | | 670 | 9 | 75 | 92 | 92 | | 215 | | 11908 | 3.849 | 0.904 |
| | NY00719 | FINCH HOLLOW WATERSHED PROJ | 42 | 8 | 75 | 57 | | 20 | 57 | 31403 | | 2032 | | 1 | | 818 | 30.876 | 1.000 |
| | NY01004 | H. F. MEYERS DAM AND DIKE | 42 | 12 | 76 | 29 | | 73 | 11 | 56 | | 4 | | 19 | | 3555 | 0.340 | 0.807 |
| | OK10499 | LAKE ARDMORE | 34 | 15 | 97 | 10 | | 570 | 25 | 1100 | | 71 | | 66 | | 6590 | 0.697 | 0.960 |
| | OK21312 | OKNONAME 149022 | 35 | 11 | 98 | 58 | | 159 | 37 | 2807 | | 182 | | 12 | | 2861 | 1.872 | 0.997 |
| | OR00615 | MARVIN FAST DAM | 45 | 3 | 123 | 13 | | 330 | 14 | | | | | 68 | | 6700 | | |
| | PA00974 | BREWSTER POND DAM | 41 | 48 | 75 | 52 | | 75 | 15 | 90 | | 6 | | 14 | | 3086 | 0.338 | 0.899 |
| | SC01648 | ALCORN DAM D-0244 | 34 | 46 | 80 | 52 | | 72 | 18 | 772 | | 50 | | 12 | | 2760 | 2.254 | 0.990 |
| | SC01326 | WRENN FARM POND DAM D-1756 | 34 | 4 | 81 | 2 | | 50 | 31 | 32 | | 2 | | 5 | | 1753 | 0.050 | 0.908 |
| | TX02151 | KNOX DAM NUMBER 3 | 32 | 1 | 99 | 20 | | 114 | 26 | | 34 | 34 | | 13 | | 2890 | 0.702 | 0.983 |
| | TX02728 | VALLEY CREEK WS SCS SITE | 32 | 12 | 100 | 12 | | 197 | 44 | 9720 | 0 | 0 | | 13 | | 2920 | 0.000 | 0.000 |
| | TX03774 | AMANDA LAKE DAM | 30 | 53 | 94 | 24 | | 971 | 26 | 3287 | 34 | 34 | 202 | 202 | 6562 | 6562 | 0.351 | 0.788 |
| | VA01527 | LOWER WALLACE DAM | 38 | 1 | 79 | 8 | | 64 | 25 | 1306 | | 85 | | 7 | | 2208 | 2.471 | 0.996 |
| | WA01317 | KEPKA LAKE DAM | 47 | 7 | 122 | 1 | | 15 | 10 | | | | | 4 | | 1690 | | |
| | WI00711 | WATER MILL | 44 | 3 | 90 | 28 | | 110 | 10 | 3300 | 58 | 58 | | 32 | | 4577 | 5.113 | 0.976 |

| RANDOM SAMPLE | DAM ID | NAME | VOLLENWEIDER CORRELATION | UPSTREAM DATA | PHOSPHORUS N | IN-POOL DATA | PHOSPHORUS N | ESTIMATE | DOWNSTREAM DATA | PHOSPHORUS N | SUMMER DATA | PNC N | WINTER DATA | PNC N | TOTAL N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SMALL | AR00419 | CANEY CREEK SITE 2 DAM | | | | | | | | | | | | | |
| | CO00612 | PEDRO | | | | | | | | | | | | | |
| | CT00646 | PARIZEK POND DAM | | | | | | | 0.115 | 15 | | | | | |
| | GA03560 | WALKER LAKE DAM | | | | | | | | | | | | | |
| | IA00765 | SITE 10-2 MCCALL SWSHED ST6 | | | | | | | | | | | | | |
| | IA01540 | LEDGEWOOD CREEK WTRSHD SITE | | | | | | | | | | | | | |
| | IA01731 | 6-5495 LUM HOLLOW SUBWTRSHD | | | | | | | | | | | | | |
| | IL01221 | MSDGC DAM NO. 9 (1975 RPRT) | | | | | | | | | | | | | |
| | IN00711 | RALPH KETCHUM LAKE DAM | | | | | | | | | | | | | |
| | KS00412 | KSNONAME 412 | | | | | | | | | | | | | |
| | KS01335 | KSNONAME1335 | | | | | | | 0.135 | 82 | | | | | |
| | KS01513 | KSNONAME 1513 | | | | | | | | | | | | | |
| | KS01702 | KSNONAME 1702 | | | | | | | | | | | | | |
| | KS03372 | KSNONAME 3372 | | | | | | | | | | | | | |
| | KS04982 | KSNONAME 4982 | | | | | | | | | | | | | |
| | KS04993 | KSNONAME 4993 | | | | | | | | | | | | | |
| | KY00271 | TYNER LAKE DAM | | | | 0.011 | 3 | 0.011 | | | | | | | |
| | KY00642 | WALLACE AND BOWLING LK DAM | | | | | | | | | | | | | |
| | MA00967 | HODGES VILLAGE | | 0.074 | 29 | | | 0.047 | 0.499 | 21 | 0.00 | 11 | - | - | 11 |
| | MI01262 | SANITATION DAM | | 0.122 | 4 | | | 0.078 | | | | | | | |
| | MO30855 | AUTUMN LAKE DAM | | | | | | | | | | | | | |
| | MT01323 | OLSEN #1 | | | | | | | | | | | | | |
| | MT01674 | POWELL #2 | | | | | | | | | | | | | |
| | NC00382 | DUPONT DAM | | | | | | | | | | | | | |
| | NE01654 | FRAHM DAM | | | | | | | | | | | | | |
| | NY00169 | MARIAVILLE LAKE DAM | | | | | | | | | | | | | |
| | NY00719 | FINCH HOLLOW WATERSHED PROJ | | | | | | | | | | | | | |
| | NY01004 | H. F. MEYERS DAM AND DIKE | | | | | | | | | | | | | |
| | OK10499 | LAKE ARDMORE | | | | | | | | | | | | | |
| | OK21312 | OKNONAME 149022 | | | | | | | | | | | | | |
| | OR00615 | MARVIN FAST DAM | | | | | | | | | | | | | |
| | PA00974 | BREWSTER POND DAM | | | | | | | | | | | | | |
| | SC01648 | ALCORN DAM D-0244 | | | | | | | | | | | | | |
| | SC01326 | WRENN FARM POND DAM D-1756 | | | | | | | | | | | | | |
| | TX02151 | KNOX DAM NUMBER 3 | | | | | | | | | | | | | |
| | TX02728 | VALLEY CREEK WS SCS SITE | | | | | | | | | | | | | |
| | TX03774 | AMANDA LAKE DAM | | | | | | | | | | | | | |
| | VA01527 | LOWER WALLACE DAM | | | | | | | | | | | | | |
| | WA01317 | KEPKA LAKE DAM | | | | | | | | | | | | | |
| | WI00711 | WATER MILL | | | | | | | | | | | | | |

| RANDOM SAMPLE | DAM ID | NAME | BOD5 | CHLA | DISSO | DOWK | FEDIS | FETOT | H2S | MNDIS | MNTOT | NITTOT | NO2NO3 | PHOS | TEMP | TKN | TURB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SMALL | AR00419 | CANEY CREEK SITE 2 DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | CO00612 | PEDRO | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | CT00646 | PARIZEK POND DAM | - | U | U-D | D | U-D | - | - | U-D | - | - | D | D | U-D | - | - |
| | GA03560 | WALKER LAKE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | IA00765 | SITE 10-2 MCCALL SWSHED ST6 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | IA01540 | LEDGEWOOD CREEK WTRSHD SITE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | IA01731 | 6-5495 LUM HOLLOW SUBWTRSHD | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | IL01221 | MSDGC DAM NO. 9 (1975 RPRT) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | IN00711 | RALPH KETCHUM LAKE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | KS00412 | KSNONAME 412 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | KS01335 | KSNONAME1335 | D | - | D | D | D | D | - | D | D | - | D | D | D | D | D |
| | KS01513 | KSNONAME 1513 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | KS01702 | KSNONAME 1702 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | KS03372 | KSNONAME 3372 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | KS04982 | KSNONAME 4982 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | KS04993 | KSNONAME 4993 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | KY00271 | TYNER LAKE DAM | - | - | - | P | - | - | - | - | - | - | P | P | P | - | - |
| | KY00642 | WALLACE AND BOWLING LK DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | MA00967 | HODGES VILLAGE | U | - | D | U-D | U-D | U-D | - | U-D | U | - | U | U-D | U-D | U | U-D |
| | MI01262 | SANITATION DAM | U | - | - | U | - | U | - | - | U | - | U | U | - | - | - |
| | MO30855 | AUTUMN LAKE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | MT01323 | OLSEN #1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | MT01674 | POWELL #2 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | NC00382 | DUPONT DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | NE01654 | FRAHM DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | NY00169 | MARIAVILLE LAKE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | NY00719 | FINCH HOLLOW WATERSHED PROJ | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | NY01004 | H. F. MEYERS DAM AND DIKE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | OK10499 | LAKE ARDMORE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | OK21312 | OKNONAME 149022 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | OR00615 | MARVIN FAST DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | PA00974 | BREWSTER POND DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | SC01648 | ALCORN DAM D-0244 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | SC01326 | WRENN FARM POND DAM D-1756 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | TX02151 | KNOX DAM NUMBER 3 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | TX02728 | VALLEY CREEK WS SCS SITE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | TX03774 | AMANDA LAKE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | VA01527 | LOWER WALLACE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | WA01317 | KEPKA LAKE DAM | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | WI00711 | WATER MILL | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

| TYPE OF SAMPLE | DAM ID | NAME | LAT/LONG D | M | D | M | POWER (100KW) | V (ac-ft) | H (ft) | QMAX (cfs) | Qave (cfs) DATA | ESTIMATE | AREA (acres) DATA | ESTIMATE | LENGTH (feet) DATA | ESTIMATE | FROUDE | RETENTION COEFF. | SUMMER DATA | PNC N | WINTER DATA | PNC N | TOTAL N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CASE | AL01408 | UPPER BEAR CREEK | 34 | 16 | 87 | 42 | | 19260 | 69 | 74600 | 262 | 262 | | 805 | 37000 | 37000 | 0.155 | 0.878 | 0.00 | 8 | 0.00 | 8 | 16 |
| STUDIES | AL01412 | GUNTERSVILLE DAM | 34 | 25 | 86 | 24 | 97 | 879700 | 74 | 650000 | 41 | 41 | 67900 | 67900 | 401000 | 401000 | 0.011 | 0.013 | 0.02 | 448 | 0.01 | 849 | 1297 |
| | CA00416 | McCLOUD DAM | 41 | 8 | 122 | 4 | | 35300 | 198 | 22000 | 541 | 541 | 520 | 520 | | 18427 | 0.030 | 0.958 | 0.00 | 6 | 0.00 | 8 | 14 |
| | CA10136 | BRADBURY DAM | 34 | 35 | 119 | 59 | | 205000 | 201 | 161000 | 63 | 63 | 3100 | 3100 | | 44075 | 0.002 | 0.310 | 0.05 | 58 | 0.01 | 136 | 194 |
| | CA10139 | CASITAS DAM | 34 | 23 | 119 | 20 | | 254000 | 279 | 7400 | 11 | 11 | | 2624 | | 41641 | 0.0001 | 0.085 | 0.00 | 9 | 0.00 | 29 | 38 |
| | GA***** | RICHARD B RUSSELL DAM | | | | | | 1030000 | | | 155 | 155 | 26700 | 26700 | | | | 0.114 | | | | | |
| | IA00013 | RED ROCK DAM | 41 | 22 | 92 | 59 | | 90000 | 79 | 378000 | 4659 | 4659 | 6300 | 6300 | 42200 | 42200 | 1.124 | 0.942 | 0.02 | 219 | 0.01 | 346 | 565 |
| | MO***** | CLARENCE CANNON DAM | | | | | | 1428000 | | | 1701 | 1701 | 18600 | 18600 | 132000 | 132000 | 0.015 | 0.669 | | | | | |
| | TN01302 | NORRIS DAM | 36 | 13 | 84 | 6 | 1008 | 630000 | 238 | 210000 | 4405 | 4405 | 34200 | 34200 | 385000 | 385000 | 0.074 | 0.740 | 0.83 | 12 | 0.04 | 27 | 39 |
| | TN03701 | J PERCY PRIEST DAM | 36 | 10 | 86 | 37 | 280 | 302000 | 120 | 263000 | 1918 | 1918 | 14200 | 14200 | | 69235 | 0.152 | 0.749 | 0.56 | 18 | 0.21 | 29 | 47 |
| | TN03702 | OLD HICKORY DAM | 36 | 18 | 86 | 37 | 1000 | 357000 | 68 | 228000 | 18876 | 18876 | 22500 | 22500 | | 99998 | 2.449 | 0.949 | | | | | |
| | TN16306 | BOONE DAM | 36 | 26 | 82 | 26 | 750 | 45000 | 153 | 137000 | 2553 | 2553 | 4310 | 4310 | 91900 | 91900 | 3.670 | 0.929 | 0.50 | 513 | 0.12 | 817 | 1330 |
| | TN16307 | FORT P HENRY DAM | 36 | 30 | 82 | 31 | 360 | 22700 | 88 | 141000 | 2593 | 2593 | 872 | 872 | 54900 | 54900 | 1.771 | 0.985 | 0.67 | 522 | 0.10 | 828 | 1350 |
| | UT10121 | FLAMING GORGE DAM | 40 | 54 | 109 | 25 | 1080 | 3789000 | 453 | 29000 | 2171 | 2171 | 42000 | 42000 | 475000 | 475000 | 0.022 | 0.533 | | | | | |
| | WI00780 | EAU GALLE DAM | 44 | 51 | 92 | 14 | | 1550 | 25 | 14500 | 99 | 99 | 150 | 150 | 3300 | 3300 | 0.150 | 0.936 | | | | | |

Note: The Richard B. Russell and the Clarence Cannon Dams were built after the COE Inventory was completed. Data for these facilities were taken from information provided in the case study chapter.

## APPENDIX C
## ANALYSIS SUPPLEMENT

This appendix summarizes some of the analysis methods employed in the technical analyses including a mixing model, a phosphorus retention model, physical attribute estimators, and a discussion on the significance of correlation, a discussion of sample size, a discussion of how representative are the random samples with respect to the population, and STORET water quality incidence summaries.

### MIXING MODEL

The densimetric Froude number represents the ratio of inertial forces imposed by the longitudinal flow to gravitational forces within an impoundment and can be written for a reservoir as (USEPA, 1969):

$$F = \frac{L \cdot q}{D \cdot V} \cdot \left[ \frac{d_o^{0.5}}{g \cdot \beta} \right]$$

where:

$L$ = reservoir length,

$q$ = average yearly discharge through the reservoir,

$D$ = mean reservoir depth,

$V$ = reservoir volume,

$d_o$ = reference density,

$\beta$ = average density gradient in the reservoir, and

$g$ = gravitational constant.

In deep reservoirs, the fact that the isotherms are horizontal indicates that the inertia of the longitudinal flow is insufficient to disturb the overall gravitational static equilibrium state of the reservoir, except possibly for local disturbances in the vicinity of the reservoir outlets and at points of tributary inflow. Thus, F would be expected to be small for such reservoirs. On the other hand, in completely mixed reservoirs, the inertia of the flow and its attendant turbulence is sufficient to completely upset the gravitational structure and destratify the reservoir. For reservoirs of this class, **F** would be expected to be large. In between these two extreme classes lies the weakly-stratified reservoir in which the longitudinal flow possesses enough inertia to disrupt the reservoir isotherms from their gravitational static-equilibrium state configuration, but not enough to completely mix the reservoir.

For the purpose of classifying reservoirs by their Froude number, β and $d_o$ may be approximated as 0.001 kg/m$^4$ and 1000 kg/m$^3$, respectively. Substituting these values and **g** leads to an expression for **F** as:

$$F = 320 \cdot \frac{L \cdot q}{D \cdot V}$$

where **L** and **D** have units of meters, **q** is in cfs, and **V** has units of m$^3$. From this equation it is observed that the principal reservoir parameters that determine a reservoir's classification are its length, depth, and discharge to volume ratio (q/V).

In developing some familiarity with the magnitude of **F** for different reservoir situations, it is helpful to note that theoretical and experimental work in stratified flow indicates that flow separation occurs in a stratified fluid when the Froude number is less than about $1/\pi$ (0.318). For example, for $F < 1/\pi$, part of the fluid will be in motion longitudinally while the remainder is essentially at rest. Furthermore, as **F** becomes smaller and smaller, the flowing layer becomes more and more concentrated in the vertical direction. Thus, in a deep reservoir, it is to be expected that the longitudinal flow is highly concentrated at values of $F \ll 1/\pi$. While in the completely mixed case, **F** must be at least greater than $1/\pi$, since the entire reservoir is in motion, and it may be expected in general that $F \gg 1/\pi$. Values of **F** for the weakly-stratified case would fall between these two limits and might be expected to be on the order of $1/\pi$.

The Froude number, written in the units found in the Corps of Engineers data base (feet, acre•feet, cubic feet per second) becomes:

$$F = 0.00735 \cdot \frac{L \cdot q}{D \cdot V}$$

The only variable in the Corps of Engineers data base that can be directly used in this formula is the reservoir volume, **V**. The other variables, **L**, **D**, and **q**, are ancillary variables and must be estimated. Estimates are derived in a following section that calculates **L** as a function of **V/H**, **D** as a function of **V/H**, and **q** as a function of **Q**. **V**, **H**, and **Q** are basic variables in the Corps of Engineers data base: normal volume, hydraulic height of dam, and spillway capacity, respectively. The estimators are shown to be statistically significant.

## PHOSPHORUS RETENTION MODEL

Although TVA recommends against using "models...assuming steady state conditions and continuous stirred tank reactor behavior" for estimating ambient phosphorus to judge TVA reservoirs, such models are common, available, and seem useful for screening on a national scale (TVA, 1983). One would not use such a model to make control decisions without considerable extra site specific study and refinement. One could use "tank reactor models" to identify the possible presence of effects, and if so, the extent of effects.

One such "tank reactor" model, attributed to Vollenweider (Vollenweider, 1975), and presented by Reckhow (USEPA, 1979), has the operational feature that it can be utilized with the Corps of Engineer's data base.

The Vollenweider model presented here can be theoretically derived from the annual phosphorus mass balance to any impoundment:

$$P_p = M \cdot \left[ \frac{1}{(V_s \cdot A) + q} \right]$$

where:

- $\mathbf{P_p}$ = the average annual phosphorus concentration in the pool of the impoundment,
- **M** = the annual total phosphorus input to the impoundment, and
- $\mathbf{V_s}$ = the "apparent" settling velocity,
- **A** = the area of the bottom of the impoundment, which is assumed equal to the normal pool surface area, and
- **q** = the average annual inflow to the impoundment.

Vollenweider implicitly identifies a constant settling velocity of $V_s$ equal to 10 meters/year. A criticism of Vollenweider's approach is that it is empiric, because $\mathbf{V_s}$ is estimated, and applies to northern temperate situations. Reckhow observes that Vollenweider's model will probably overestimate $\mathbf{P_p}$ when high surface overflow rates, **Q/A**, are present, and underestimate $\mathbf{P_p}$ in lakes that are highly enriched. Reckhow discusses model refinements that allow $\mathbf{V_s}$ to vary.

However, the Vollenweider model is dimensionally sound and is only empirical with respect to selection of $\mathbf{V_s}$. Furthermore, it explains a significant amount of the variance, $\mathbf{R^2}$, associated with TVA samples (44 percent) and associated with sampling data in this report (51 percent).

These $R^2$ values are discussed in detail later in this appendix. Thus, although elementary, the Vollenweider has a place in screening reservoirs and evaluation of national eutrophication potential.

The Vollenweider model is transformed to a more useful form by dividing **M** by **q** and multiplying the terms in bracket by **q**. This approach results in an expression of the Vollenweider model that multiplies the input average phosphorus concentration (**M/q**) by a dimensionless retention coefficient, **e**. The transformed model is given as:

$$P_p = \frac{M}{q} \cdot \left[ \frac{q}{(V_s \cdot A) + q} \right]$$

Substituting $P_i$, the average annual phosphorus concentration of input flow to the impoundment, for the quotient **M/q** yields:

$$P_p = P_i \cdot \left[ \frac{q}{(V_s \cdot A) + q} \right]$$

The retention coefficient, **e**, is given as:

$$e = \left[ \frac{q}{(V_s \cdot A) + q} \right]$$

The formula of the retention coefficient, **e**, for **q** (units of cfs) and **A** (units of acres), assuming $V_s$ = 10 meters/second, is

$$e = \left[ \frac{q}{(0.0453 \cdot A) + q} \right]$$

Thus, if $V_s$ is unbiased, a value of **e** = 0.33 implies that the average inpool lake phosphorus concentration is 33 percent of the phosphorus concentration of reservoir inflow waters. The possible bias is a concern, but not a fatal flaw of this model, as long as it is identified and adjustments are made.

To sum up, one can estimate $P_p$ directly or by using the Vollenweider retention coefficient times the input phosphorus concentration. The estimate uses a prediction that captures a significant amount of the variation. The prediction is biased by the use of northern temperate situations to establish $\mathbf{V_s}$, and the bias can be dealt with by quantifying it in the application to reservoirs in the United States. Once $\mathbf{P_p}$ is estimated, the EPA criterion of 0.025 mg/l for phosphorus can be used to evaluate the potential for eutrophication. Furthermore, this approach is useful only for screening purposes. As such, the progression to more detailed analyses is necessary to evaluate specific sites and to specify need for and type of mitigation.

## PHYSICAL ATTRIBUTE ESTIMATORS

The Corps of Engineers data base contains the following basic data elements:

**V** = the normal pool volume (acre•feet),

**H** = the hydraulic height of the dam (feet), and

**Q** = the spillway capacity of the dam (cfs).

As discussed earlier, the mixing model estimates the Froude number, **F**, using the following independent variables, **L**, **D**, **q**, and **V**. Volume is the only variable contained in the basic data. The Vollenweider model estimates the phosphorus retention coefficient, **e**, using the independent variables, **q** and **A**, neither of which are contained in the basic data. Therefore, to estimate **F** and **e**, using the Corps of Engineers data base, estimates of **L**, **D**, **q**, and **A** as functions of **V**, **H**, and **Q** are necessary.

To secure such estimates, ancillary data for **L**, **A**, and **q** are developed for subsets of the random sample of dams. For reasons of confidence, a sample of at least 30 out of the 120 random dams, plus case study dams given in Appendix B, is desired. The following methods are used:

- for **L** and **A**, the length and surface area of the impoundment are measured using a USGS topographic map. The variables are converted to units of feet and acres.

- for **q**, the average annual flow is taken from the Reach File mean flow data. The Reach File is linked to STORET and is an EPA in-house data file. The unit of **q** is cfs.

- **D**, the average depth, is computed by dividing **V** by **A**. The unit of **D** is feet.

The ancillary data for **L**, **A**, and **q**, for the several sites for which these data are estimated, are presented in Appendix B. The site selection involved application of engineering judgement to spread the sites around the United States and across power and nonpower dams.

Once obtained, least squares, linear regression analysis is performed to estimate the fit. The models are specified, *a priori*, to be dimensionally sound and are constrained to have zero intercepts to give logical functional relationships that are applicable to small dams.

Thus, **q** is estimated from **Q**. **A** is estimated from **V/H**; and **L** is estimated from the square root of **V/H**. The linear regressions, sample sizes, and percentages of explained variation, $R^2$, are:

$$q = 0.0647 \cdot Q \quad (n = 64,\ R^2 = 0.61),$$

$$A = 2.88 \cdot \frac{V}{H} \quad (n = 30,\ R^2 = 0.59), \text{ and}$$

$$L = 6.61 \cdot \left[ \frac{43560 \cdot V}{H} \right]^{0.5} \quad (n = 30,\ R^2 = 0.47).$$

The units are in cfs for **q** and **Q**, acres for **A**, and feet for **L** and **H**.

The three regressions are statistically significant and are used to estimate **F** and **e**. A discussion of the significance of $R^2$ follows.

## SIGNIFICANCE OF CORRELATION

The correlation coefficient, **R**, measures the strength of a linear relationship between two variables. For **R = 1**, the relationship is exactly linear whereas **R = 0** indicates no relationship. Therefore, as **R** approaches unity, a linear relationship approaches exactitude.

The square of the correlation coefficient, $R^2$, measures the percentage of the variation of a dependent variable that is explained by its linear relationship with an independent variable. Variation is defined in statistical terms as variance which is the square of the standard deviation.

Therefore, if **SD(y)** is the standard deviation of a random variate, **y**, and **SE(y|x)** is the standard error of predictions associated with a least squares regression of **y** on **x**, a dependent variable, then the percentage of explained variation is expressed as:

$$R^2 = \frac{[SD(y)]^2 - [SE(y|x)]^2}{[SD(y)]^2}$$

The difference in the numerator is the variance or variation that is conditionally explained by the least squares regression of **y** and **x**. The square root of $R^2$ is considerably less than **R**.

How does one judge the significance of $R^2$ with respect to sample size **n**? Kendall presents a logarithmic transform of **R** that approaches normality (Kendall and Stuart, 1963). The transform, attributed to Fisher, is given as:

$$z = 0.5 \cdot \log_e \left[ \frac{1 + R}{1 - R} \right]$$

whose standard deviation is:

$$SD(z) = 1 / (n - 3)^{0.5}$$

Because **z** tends to normality, the normal probability distribution can be used to test the hypothesis that **R** is rot equal to zero, and hence, a relationship is significant. At the 95 percent confidence interval, the following values of $R^2$, depicted below in Table C-1, are necessary to infer that a relationship is significant using Fishers' z.

Table C-1. Sample Sizes for 95% Significant $R^2$.

| **n**, sample size | $R^2$ above which **R** can be deduced to be nonzero, and hence, significant, with 95 percent confidence. |
|---|---|
| 10 | 40% |
| 15 | 26% |
| 20 | 20% |
| 25 | 16% |
| 30 | 13% |
| 40 | 10% |
| 50 | 8% |
| 100 | 4% |

To place correlation results presented in this report into context, the various $R^2$s and sample sizes are summarized in Table C-2.

Table C-2. Significance of Elementary Models.

| Relationship | $R^2$ | n | 95% Confidence |
|---|---|---|---|
| q vs Q ** | 61% | 64 | Significant |
| A vs [V/H] ** | 59% | 30 | Significant |
| L vs $[V/H]^{0.5}$ ** | 47% | 30 | Significant |
| δTemp vs Froude F* | 68% | 22 | Significant |
| Measured P vs Vollenweider * | 44% | 11 | Significant |
| Measured P vs Vollenweider ** | 51% | 22 | Significant |

* TVA Data.
** Relationships derived in various sections of this report.

**SAMPLE SIZE**

Is a sample of 40 dams adequate to represent the finite population of 424 large power dams? For estimating the effects of dams, the goal is to find how many dams have significant effects and how many do not. The answer depends upon statistical reasoning. The statistician asks the question: What sample size will provide given confidence intervals?

In other words, once you take your sample of **n**, you want to be 95 percent certain (that is, you want the estimate to be right 19 out of 20 times if you would repeat the random sample 20 times) that your answer is within a particular error bound.

This problem can be theoretically formulated, like a coin tossing experiment, with the Hypergeometric distribution. The error bound at 95 percent certainty is approximately plus or minus two standard deviations of the standard deviation of the Hypergeometric distribution because it approaches normality (Kendall and Stuart, 1963).

The standard deviation of the Hypergeometric distribution is:

$$SD = \left[ n(p) \cdot (1 - p) \cdot \left[ \frac{N - n}{N - 1} \right] \right]^{0.5}$$

where:

**n** = number of random samples,

**p** = fraction of the population having a particular attribute; for example, p = 0.5 indicates 50% of the population possesses the attribute, and

**N** = the size of the finite population.

Applying this Hypergeometric formulation to the sample of 40 large power dams out of the total population of 424 of such dams, assume the attribute of interest has a frequency of 50 percent or **p** = 0.5. Thus, the assumption is that low dissolved oxygen in tailwaters, for example, is present in 50 percent of all large power dams. For this assumption, the standard deviation of the Hypergeometric distribution is 3 dams. Twice the standard deviation is 6 dams. The expected number of dams is **p** x **n** which for a sample of 40 with **p** = 0.5 is 20.

Therefore, out of a sample of 40 of a population with an attribute with 50 percent frequency, one would expect between 20 - 6 and 20 + 6 dams (the expected value plus or minus two standard deviations) to possess the attribute with 95 percent confidence. In other words, the 95 percent confidence range is 14 to 26 dams. A random sample of 40 would fall within this range with 95 percent certainty. With the same logic a random sample of 40 would fall within a range of 15 to 25 with 90 percent certainty.

With regard to the need for partitioning the population into the three subsets, large power, large nonpower, and small: assume that an attribute is frequent in a small subset and infrequent in the entire population. For example, let the small subset be the 424 large power dams and the population be the 68,155 dams. Further, assume the attribute frequency is 50 percent of the large power dams and 2.5 percent of the population; the attribute of significant dissolved oxygen change in dam tailwaters is a good example having high subset frequency and presumed low population frequency. Thus, the partitioning places the attribute in a subset sample range of 14 to 26 dams with **n** = 40, but a representation of the attribute in the larger population, with 95 percent confidence, implies a range of 0 to 3 with a high probability on 0. To sum up, the number of 40 random subset dams possessing the attribute would fall in the range 14 to 26, and the number of 40 random population dams in the range 0 to 3. One would stand a sizable chance of not identifying the attribute at all in a sample of 40 of the population.

## SAMPLE REPRESENTATIVENESS

Do the forty dams distributed in each of three samples adequately reflect the locational distribution of the associated population? The samples are classified by geographic region. The first region, Northeast, is defined as EPA regions I, II, III, and V. The second region, designated as South, contains EPA regions IV and VI. The final region, West, is defined as EPA regions VII, VIII, IX, and X. The comparison of the samples and the populations are illustrated in Table C-3. Generally, it can be seen that the proportion of the observations in sample regions are approximately equal to those of the population regions.

Table C-3.
Summary of Geographic Distribution.

| | REGION | | | |
|---|---|---|---|---|
| CLASSIFICATION | Northeast | South | West | Total |
| Large Power | | | | |
| Sample | 8 (20%) | 15 (38%) | 17 (42%) | 40 |
| Population | 110 (26%) | 139 (33%) | 175 (41%) | 424 |
| Large Nonpower | | | | |
| Sample | 16 (40%) | 11 (28%) | 13 (32%) | 40 |
| Population | 589 (35%) | 488 (29%) | 624 (36%) | 1701 |
| Small Dam | | | | |
| Sample | 11 (28%) | 12 (30%) | 17 (42%) | 40 |
| Population | 15478 (23%) | 25320 (38%) | 25232 (39%) | 66030 |

Do the sample frequency distributions represent the population frequency of all dams in each partitioned subset? The Kolmogorov-Smirnov (KS) test is applied to answer this inquiry (Kendall and Stuart, 1963). Figure C-1 shows the cumulative distributions of **V** (normal pool volume) of the population and the sample for large power dams. On the vertical axis is the cumulative frequency or probability. The cumulative frequency times 100 represents the "percent equal to or less than." The horizontal axis for Figure C-1 represents the volume.

The KS test involves determining the maximum vertical distance between two frequency curves such as illustrated in Figure C-1. For example, for the large power sample and population distribution, the maximum vertical distance is 0.15 cumulative probability units. The value 0.140 is the KS test statistic. If this statistic is less than the value 0.210 (the cumulative probability units associated with a sample size of 40 and a significance level of 95 percent), the sample and population distributions are statistically similar.

In other words, the KS test compares the continuous distribution of a population to the continuous distribution of a sample. The maximum difference between the two distribution functions is itself a distribution as a function of sample sizes and significance levels. The value of the maximum difference distribution is compared to tabulated values of this distribution for various sample sizes and levels of significance. If the level of significance value is greater than the maximum difference, the sample is a representative, significant sample of the population. The distributions are checked with the KS test for volume, Froude number, phosphorus retention coefficient, and installed power. The results are depicted in Table C-4.

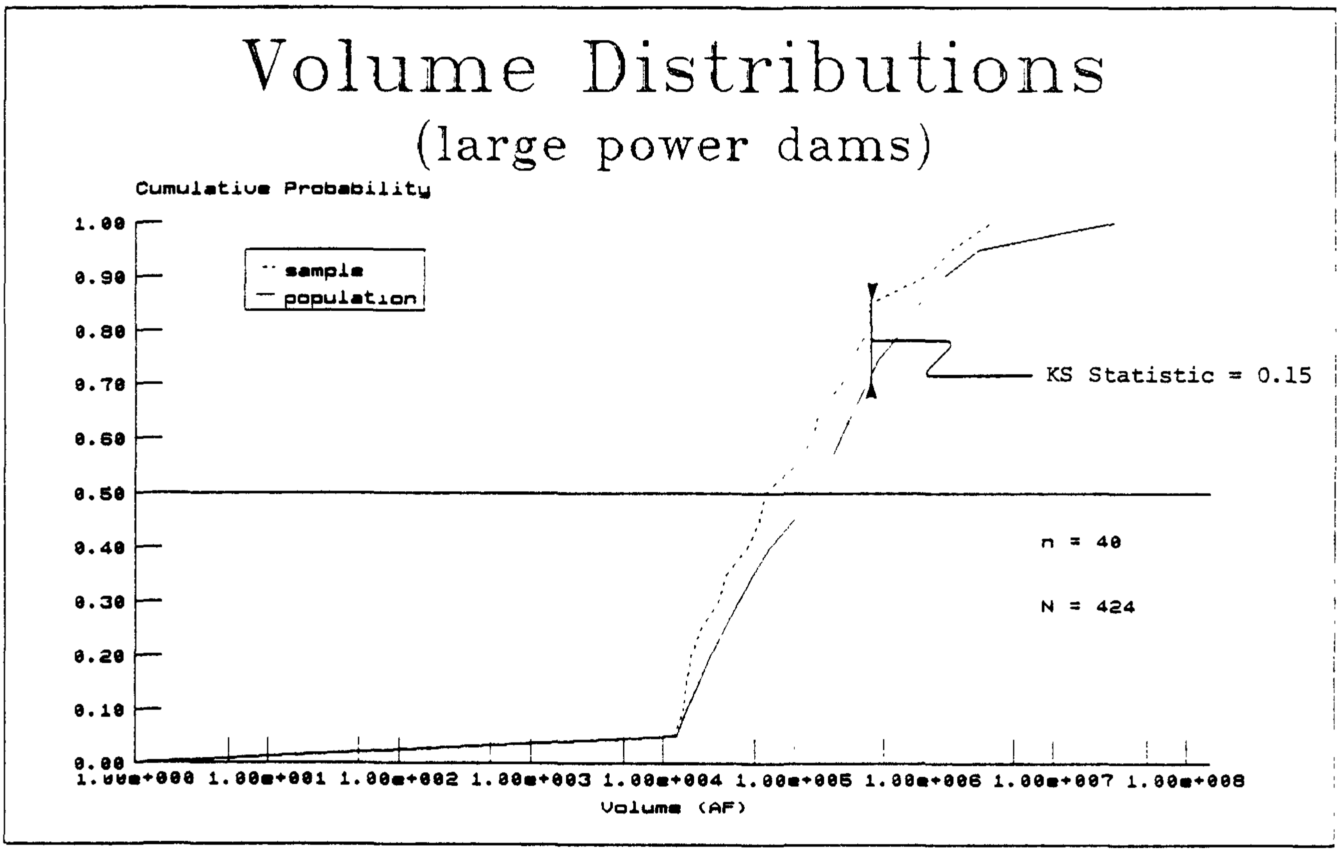


Figure C-1.
Volume Distributions (large power dams)

Table C-4.
Results of the KS Test for Sample Distributions.

| Distribution | KS Test Statistic | KS 95 Percent Significant Level |
|---|---|---|
| Normal Volume (V) | | |
| 1. Large Power | 0.15 | 0.21 |
| 2. Large Nonpower | 0.14 | 0.21 |
| 3. Small Combined | 0.17 | 0.21 |
| Froude Number | | |
| 4. Large Power | 0.13 | 0.21 |
| 5. Large Nonpower | 0.15 | 0.21 |
| 6. Small Combined | 0.14 | 0.21 |
| Phosphorus Retention Coefficient (e) | | |
| 7. Large Power | 0.12 | 0.21 |
| 8. Large Nonpower | 0.10 | 0.21 |
| 9. Small Combined | 0.12 | 0.21 |
| Installed Power | | |
| 10. Large Power | 0.12 | 0.21 |

Note: All 10 distributions are significant at 95 percent level.

## STORET WATER QUALITY RETRIEVAL SUMMARIZATIONS

This section presents information on the STORET parameters and the incidence of data at the three classes of dams and the incidence of water quality observations at dams for which data are present. Table C-5 presents the water quality parameters.

Tables C-6 and C-7 illustrate the distribution of the data for each of the three categories, (L-P, L-NP, S), at upstream (U), downstream (D), and Pool (P) locations. Table C-6 shows the number of dams reporting data. The large power dams have the largest average number of observations per parameter. The large nonpower dams are next. The data for small dams are sparse. Table C-7 shows the average numbers of observations per dam.

Table C-5.
Water Quality Parameters.

| Parameters | Storet # | Units | Parameters | Storet # | Units |
|---|---|---|---|---|---|
| Fishkill | 1340 | dead fish | Water Temperature | | |
| | | | Celsius | 10 | degrees |
| Stream Flow | | | | | |
| Mean Daily | 60 | cfs | Iron (Fe) | | |
| | | | Dissolved | 1045 | ug/l |
| Dissolved Oxygen | | | Total (as Fe) | 1046 | ug/l |
| Probe | 299 | mg/l | | | |
| Winker | 300 | mg/l | Manganese | | |
| | | | Dissolved | 1056 | ug/l |
| Phosphorus | | | Total | 1055 | ug/l |
| Total (as P) | 665 | mg/l | | | |
| | | | Hydrogen Sulfide | | |
| Nitrogen | | | as $H_2S$ | 71875 | mg/l |
| Total (as N) | 600 | mg/l | | | |
| TKN | 625 | mg/l | Chlorophyll A | | |
| $NO_3 + NO_2$ | 630 | mg/l | as Chl-a | 32230 | mg/l |
| Turbidity | | | $BOD_5$ | 310 | mg/l |
| Jackson Candle | 70 | mg/l | | | |
| | | | Dissolved Solids | 70301 | mg/l |

Table C-6.
Number of Dams Reporting Data.

| | Upstream (U) | | | Pool (P) | | | Downstream (D) | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter* | L-P | L-NP | S | L-P | L-NP | S | L-P | L-NP | S |
| DO | 33 | 10 | 2 | 23 | 14 | 1 | 33 | 12 | 3 |
| Manganese Total | 22 | 9 | 2 | 12 | 8 | 0 | 19 | 9 | 1 |
| Iron Total | 24 | 9 | 2 | 11 | 9 | 0 | 22 | 10 | 2 |
| Nitrogen Total | 19 | 4 | 0 | 7 | 3 | 0 | 12 | 2 | 0 |
| TKN | 30 | 10 | 1 | 19 | 12 | 1 | 27 | 11 | 2 |
| Phosphorus | 28 | 11 | 2 | 22 | 13 | 1 | 27 | 11 | 3 |
| Temperature | 33 | 12 | 3 | 24 | 14 | 1 | 33 | 13 | 3 |

*Data were found for other parameters, but much less frequently.

Table C-7.
Average Number of Observations per Dam
for Dams Reporting Data.

| Parameter* | Upstream (U) | | | Pool (P) | | | Downstream (D) | | |
|---|---|---|---|---|---|---|---|---|---|
| | L-P | L-NP | S | L-P | L-NP | S | L-P | L-NP | S |
| DO | 596 | 232 | 6129 | 693 | 464 | 45 | 331 | 215 | 111 |
| Manganese Total | 330 | 34 | 102 | 104 | 82 | - | 57 | 71 | 2532 |
| Iron Total | 310 | 63 | 110 | 102 | 94 | - | 61 | 895 | 66 |
| Nitrogen Total | 292 | 35 | - | 83 | 49 | - | 56 | 22 | - |
| TKN | 269 | 122 | 2 | 147 | 90 | 3 | 86 | 85 | 95 |
| Phosphorus | 358 | 288 | 16 | 157 | 89 | 3 | 142 | 115 | 39 |
| Temperature | 656 | 491 | 171 | 693 | 995 | 45 | 343 | 209 | 120 |

*Data were found for other parameters, but much less frequently.

# APPENDIX D
# LARGE NONPOWER DAM SUPPLEMENT

The large nonpower dams classification consists of 1701 dams with over 10,000 acre•feet of storage at the normal pool elevation with no reported installed power. These dams may or may not have low level outlets which transmit water quality effects downstream.

Four analytical efforts were performed on large nonpower dams for this report: Mixing Analysis; Dissolved Oxygen Concentrations in Dam Tailwaters; Upstream/Downstream Comparisons; and Phosphorus Enrichment Analysis. The mixing analysis is presented in Chapter III, but the other three efforts are presented here because insufficient data were available to draw conclusions based on these analyses.

## MIXING ANALYSIS

These results are presented in Chapter III based on numbers of dams with $F < 0.3$.

## DISSOLVED OXYGEN IN DAM TAILWATERS

This method of analysis, described in detail in Chapter III, is based upon a U.S. Department of Energy supported study done by the Oak Ridge National Laboratory. Probabilities of non-compliance, i.e., the probabilities that dissolved oxygen concentrations in the tailwaters of dams will drop below 5 mg/l, were determined by the Oak Ridge Laboratory for TVA dams, and using the same methodology, the results of this analysis for large nonpower dams is presented in Table D-1.

## UPSTREAM/DOWNSTREAM COMPARISON OF WATER QUALITY

This analysis, described in detail in Chapter III, involved the collection of water quality data on sample dams from STORET, and the comparison of up and downstream data for each site, when available. The results of comparing water quality means for large nonpower dams are presented in Table D-2. Twenty-five percent, or less, of the random sample have water quality data both upstream and downstream of the impoundment.

Table D-1.
Probabilities of Non-Compliance with 5 mg/l Dissolved Oxygen
for Large Nonpower Dams.

| Summer Season | | |
|---|---|---|
| Location | n | PNC |
| Great Basin | - | - |
| Great Plains | 1 | 0.020 |
| Hawaii | - | - |
| Lake States | - | - |
| Northeast | 2 | 0.000 |
| Ohio Valley | 3 | 0.033 |
| Pacific Coast | 7 | 0.073 |
| Rocky Mountain | 1 | 0.070 |
| Southeast | 1 | 0.000 |
| Mean | | 0.033 |

| Winter Season | | |
|---|---|---|
| Great Basin | - | - |
| Great Plains | 1 | 0.010 |
| Hawaii | - | - |
| Lake States | - | - |
| Northeast | 2 | 0.010 |
| Ohio Valley | 3 | 0.000 |
| Pacific Coast | 7 | 0.027 |
| Rocky Mountain | - | - |
| Southeast | 1 | 0.000 |
| Mean | | 0.009 |

Table D-2
Tallies of Water Quality Changes
In Large Nonpower Dams

| Parameter | Dams Lacking Necessary Data | Dams with Upstream and Downstream Data | | | |
|---|---|---|---|---|---|
| | | Total Having Data | Significant Increase | Significant Decrease | Insignificant** |
| Temperature | 30 | 10 | 4 | 3 | 3 |
| Dissolved Oxygen | 31 | 9 | 3 | 4 | 2 |
| Dissolved Oxygen* | 31 | 9 | 0 | 2 | 7 |
| Iron | 34 | 6 | 2 | 2 | 2 |
| Manganese | 36 | 4 | 2 | 0 | 2 |
| Phosphorus | 31 | 9 | 2 | 2 | 5 |
| TKN | 31 | 9 | 1 | 2 | 6 |
| Total Nitrogen | 38 | 2 | 1 | 0 | 1 |

* nearest station to dam
** indicates no change in water quality

**PHOSPHORUS ENRICHMENT ANALYSIS**

The results of the phosphorus enrichment analysis, described in detail in Chapter III, for large nonpower dams are as follows. Of the forty sample dams, 24 had no phosphorus data whatsoever, seven had inpool phosphorus concentration less than the suggested EPA "Gold Book" guidance value of 0.025 mg/l, while nine had concentrations greater than 0.025 mg/l.

## APPENDIX E
## SMALL DAM SUPPLEMENT

The small dam classification consists of 66,030 dams with less than 10,000 acre•feet of storage. Four analytical efforts were performed for this report: Mixing Analysis; Dissolved Oxygen Concentrations in Dam Tailwaters; Upstream/Downstream Comparison; and Phosphorus Enrichment Analysis. The results of these analyses follow.

### MIXING ANALYSIS

The mixing analysis, explained in detail in Chapter III, categorizes the stratification potential in the impoundments. The spillway design for small dams may be based on different criteria than large dams. One criteria utilizes the maximum probable flood (U.S. Dept. of the Interior, 1977). Furthermore, it appears that many designs of small dams use standard designs (such as a 24-inch outlet pipe) for a wide range of hydrologic conditions. Design criteria could result in highly variable maximum spillway discharges which would, in turn, result in an undesirable variation in the Froude number. These small dam Froude numbers may not accurately predict the mixing potential of small impoundments.

However, the linear estimate of average flow is dimensionally sound and has been constrained to a zero intercept to allow estimates for small values. Also there are several small dams in the data utilized to develop the linear estimate. With these various qualifications, the numbers of small dams with $F < 0.3$, the TVA suggested criteria, is 9954 out of 66,030 dams; data are missing (F could not be calculated) for 18,143 dams.

### DISSOLVED OXYGEN IN DAM TAILWATERS

This analysis was not performed for small dams.

### UPSTREAM/DOWNSTREAM COMPARISON OF WATER QUALITY

There are 66,030 "small" dams having less than 10,000 acre•feet of normal pool volume comprising 96.8 percent of the population of Corps of Engineers dams. Although the maximum normal volume is 10,000 acre•feet, the median normal volume is 70 acre•feet, and one of the lower limits (the other being dam height) of the Corps of Engineers 1980 census is a pool volume of 50 acre•feet. Thus, about half the small dam population have volumes less than 70 acre•feet. On the average, these dams are 100

1/100th the size of the largest "large" dam in the partitioned sample. That is, the "large" dams start at 10,000 acre•feet, and the small dams are typically 100 acre•feet - a 100-fold difference.

Of the 40 small random dams in the sample, only 5 had some form of water quality data. Therefore, there is very little water quality monitoring evidence to indicate the effects of small impoundments. Since monitoring resources are usually focused on problem areas, lack of monitoring may suggest that either a site has no water quality problems, or that the water quality extent of the site effects is limited.

One can ask the question, how do small impoundments behave? This question arose in the 1970s relative to concerns for filing EIS documents to support new dam construction. Several intensive SCS studies in the southeast (Moore, 1973; SCS, 1978; SCS, 1987) provide site specific answers.

In Arkansas, a 4000 acre•feet water supply reservoir 20 feet deep, on the average, is strongly stratified. The Prairie Grove Lake showed extensive periods of zero dissolved oxygen in the hypolimnion combined with resulting solution of iron and manganese (Moore, 1973). The concern is the utility of the impoundment for municipal water supply. A masters' thesis (Kerr, 1977) followed up by experimenting with bottom withdrawals to unsuccessfully promote impoundment mixing. Apparently, however, low dissolved oxygen hypolimnetic waters are aerated in the splash following freefall down a morning glory spillway - essentially a vertical pipe with an elbow at the base leading to a horizontal discharge pipe which passes through the dam. Kerr fabricated a shroud to fit over the vertical pipe to allow bottom withdrawals. The withdrawals splash at the elbow.

This form of small dam release detail, a vertical pipe with an outlet elbow, is common in dams built following SCS suggestions, as is the elbow splash and resultant aeration. Thus, in general, small morning glory spillways, whether or not they handle bottom or surface waters, apparently provide aeration to tailwaters.

Extensive data gathering at four small impoundments in Mississippi provide insight to small impoundment behavior (SCS, 1978). The four projects have average water depths of 6 to 40 feet and volumes of about 200 to 8000 acre•feet. All of them stratified creating anoxic hypolimnions. If they had surface releases (3 out of 4), the tailwaters are warmer than inflows and have higher dissolved oxygen. The behavior is consistent with a theory of surface warming and either algal oxygen production or splash aeration of discharges, or both. The one impoundment with low level outlets had low dissolved oxygen, iron, and manganese in solution.

Thus, it appears that small impoundments can and do have poor quality hypolimnetic waters. If they have low level outlets, these waters are transmitted downstream. In the Mississippi studies, 1 out of 4 dams had low level outlets. A further insight is the 4 Mississippi sites all had high levels of phosphorus in their inflows and impoundments. This may be a characteristic of rural, agricultural regions having small impoundments. In a watershed management context, such small impoundments may filter phosphorus out of runoff and aid the phosphorus control in downstream dams.

In Alabama, a study of the influence of flood control impoundments on water quality by the SCS provides additional insight into small dams (SCS, 1983). In Alabama, there are more than 80 structures which discharge only surface waters, but there are only two which normally release flows from the cooler bottom waters. The incidence of low level outlets is 2 out of 80 for small Alabama flood control dams. The Alabama impoundments tended to be stratified with a noticeable difference in dissolved oxygen and temperature - top to bottom. The surface releases tended to be warmer, as reported for the four Mississippi dams.

Specific details of the five random small dams provide the reader with additional insights into the small dam situation. For example, one of the random dams is a "dry" dam holding water only during floods. At least one percent (742) of the small dams in the Corps of Engineers data base are of this type. Up to an additional two percent (1137) could also be dry dams because normal storage volumes are not recorded in the Corps data base. Dry dams and, for that matter, many navigation[1] projects, are not expected to cause significant downstream water quality problems. Additional details of the five random small dams follow (water quality data are summarized in Appendix B):

**Parizek Pond Dam: CT00646**

Parizek Pond dam, completed in 1870, impounds Parizek Pond. The dam is located at 41°52.9' latitude and 72°17.3' longitude in Willington County, Connecticut. The dam is of earthen, gravity construction with a structural height of 15 feet and a hydraulic height of 12 feet. The length along the crest of the dam is 400 feet with an uncontrolled spillway 11 feet wide. A maximum flow of 30 cfs empties into Conant Brook from the impoundment. The maximum storage capacity of the impoundment is 61 acre•feet with a normal volume of 56 acre•feet. The major purpose of the dam is to provide recreational opportunities. The dam and impoundment are privately owned and maintained by William and Mary Parizek. The data on record pertaining to Parizek Pond comes from 8 stations, 3 downstream and 3 upstream. The data indicate a low level of dissolved oxygen downstream below 5 mg/l and nutrient enrichment (mean

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[1]A total of 130 dams in the Corps data base are denoted as having one or more locks, while a total of 329 dams are reported to serve a navigational purpose. The data base appears to be incomplete and inconsistent on this point. The Corps of Engineers (Kennedy and Gaugush, 1987) state that lock and dams comprise 26 percent of 783 Corps water resources projects, or approximately 200. Furthermore, the 130 locks and dams in the Corps safety inventory are not a subset of the 329 reporting a navigation purpose.

phosphorus concentration of 0.12 mg/l) may be found downstream. No statistical difference between upstream and downstream temperatures is observed at the 90 percent confidence level.

**KSNONAME 1335: KS01335**

The dam, located at 38°26.7' latitude and 96°20.5' longitude in Chase County, Kansas, was completed in 1967. The earth construction dam has a structural height of 16 feet and a hydraulic height of 15 feet, restraining an unnamed small stock or farm pond. The crest length of 620 feet contains an uncontrolled spillway discharging a maximum flow of 636 cfs into Beaver Creek. The maximum storage capacity of the pond is 83 acre•feet with a normal volume of 42 acre•feet. The dam is owned by Kellam and regulated by DWR. The recorded data comes from 12 downstream stations. The data indicate a mean dissolved oxygen content downstream above 5 mg/l and possible nutrient enrichment downstream. Iron and manganese levels are high downstream, well over the maximum threshold.

**Tyner Lake Dam: KY00271**

Tyner Lake Dam, located at 37°22.6' latitude and 83°54.8' longitude in Jackson County, Kentucky, impounds the Flat Lick Creek Reservoir. The dam was completed in 1969 and is of earth construction with a structural height of 69 feet and a hydraulic height of 67 feet. The dam has a crest length of 1030 feet with an uncontrolled spillway 100 feet wide, discharging a maximum flow of 3207 cfs into Flat Lick Creek. The maximum storage capacity of the reservoir is 3250 acre•feet with a normal volume of 2365 acre•feet. The system is intended to provide a source of water as well as serving as a recreational facility. It is owned and maintained by the Jackson County Water Association. The data recorded comes from 1 station in the pool. These data indicate a dissolved oxygen content marginally below 5 mg/l and low phosphorus levels.

**Hodges Village Dam: MA00967 (Dry Dam)**

The Hodges Village Dam, completed in 1959, impounds Hodges Village Pond. The dam, located at 42°07.2' latitude and 71°52.8' longitude in Oxford County, Massachusetts, is primarily of earth construction with rockfill and gravity design, with a structural height of 55 feet and a hydraulic height of 50 feet. The crest length is 2050 feet with an uncontrolled spillway 145 feet in width discharging a maximum flow of 25,800 cfs into the French River. The maximum storage capacity of the impoundment is 26,000 acre•feet with a normal volume of 0 acre•feet. This dam was constructed for flood control purposes as indicated by the normal storage volume.

**Sanitation Dam: MI01262**

The dam, located at 42°31' latitude and 84°39' longitude in Ingham County, Michigan, was completed in 1918. It is a gravity-type structure with a hydraulic height of 2 feet. The crest length is 150 feet with a 130 feet spillway which discharges into the Grand River. The unnamed impoundment has a normal storage capacity of 8 acre•feet. This dam is apparently below Corps of Engineers thresholds for safety reporting, and its presence in the data base may indicate overzealousness on the part of the census taker. The dam is owned and regulated by the City of Eaton Rapids. Three upstream stations provide data on water quality. These data indicate an upstream dissolved oxygen content above 5 mg/l, phosphorus enrichment upstream, and high iron and manganese content.

The situation for small dams is water quality data are only present for 12.5 percent (or 5) of the random sample of small dams. However, site specific studies in Arkansas, Mississippi, and Alabama all indicate:

- Small dams stratify and develop anoxic epilimnions.
- Small dams with surface outlets tend to have higher dissolved oxygen and temperature in tailwaters than in inflows.
- Small dams with low-level outlets show decreasing dissolved oxygen downstream and the presence of iron and manganese.
- The incidence of low-level outlets is low in the site specific situations investigated: 1 low-level outlet in 4 Mississippi sites and 2 low-level outlets in over 80 Alabama sites.
- The typical morning glory vertical outlet with 90° outlet elbow seems to generate a splash at the elbow that aerates the tailwaters.

## PHOSPHORUS ENRICHMENT ANALYSIS

The results of the phosphorus enrichment analysis as described in Chapter III are rather sparse. For small dams, the random sample of 40 only had 4 dams with pool estimates of phosphorus. Of these four, 3 had phosphorus levels over the 0.025 mg/l critical threshold. The 4 Mississippi dams with site specific data all had high pool concentrations of phosphorus. They also had high inflow concentrations of phosphorus. Small dams are higher in watersheds and nearer to nonpoint sources of enrichment. They also tend to filter or "screen out" the phosphorus concentrations with the result that downstream inputs of phosphorus to larger dams is less than the setting when small dams are absent.

## REMARKS

The analysis of small dams is hampered by a lack of monitoring data. However, the following items are enlightening:

- The small dams are only half as likely to stratify and thus be poorly mixed based on population estimates.

- Site specific studies in the southeast do show that small dams stratify. Low-level outlets from small dams are associated with tailwater water quality effects. Surface outlets exhibit tailwaters with increased dissolved oxygen and temperature.

- The incidence of low-level outlets in small dams appears to be low in small dams - on the order of less than 3 percent for a sizable sample in Alabama.

Insufficient data are obtained to draw quantitative conclusions pertaining to small dams. What evidence exists quantitatively, points to a situation of widespread enrichment of small dam reservoirs.

APPENDIX F

# CORPS OF ENGINEERS WATER RESOURCE PROJECTS WATER QUALITY ASSESSMENT SUPPLEMENT

## GENERAL

The U.S. Army Corps of Engineers, as one of the principle Federal water resource development agencies, owns and operates over 700 water resource projects consisting primarily of reservoirs and locks and dams. The Corps civil works responsibilities began with an Act of Congress in 1824 for the improvement of rivers and harbors for navigation. Other acts expanded the legislative basis for Corps participation in the various functional areas of water management.

Today, the Corps carries out a comprehensive water resources planning, engineering, construction and operations effort in close cooperation with government agencies at all levels and a wide variety of civic and private interests. This program involves coordinated management of water resources in a manner that addresses all water-related requirements, both immediate and long-range. These requirements include flood control, navigation, hydropower, water supply, water quality, recreation, and fish and wildlife enhancement. The allocation of storage and authorities to regulate these projects are specified in legislative authorization acts for specific Corps projects, as well as project and reservoir system documents.

Inceased public concern for the environment and recognition that natural resources are both interrelated and finite, resulted in the incorporation of considerations other than economic efficiency into legislation for water recource development and management. Environmental considerations such as water quality improvement and management, and fish and wildlife requirements, were manadated by legislation, and are incorporated into authorized project purposes and operating plans, as well as Corps of Engineers regulations.

Water control policy and management in the Corps of Engineers has undergone significant changes in response to evolving environmental concerns. Many of these changes have been directly in response to Federal environmental legislation. Reservoir design and operation activities which once focused solely on quantitative aspects, are now sensitive to broader environmental considerations. Water quality is an important consideration during all phases of Corps project development, and an integral part of the decision processes related to reservoir operations.

Water control management programs provide the means for operating Corps projects to meet their authorized purposes. Most of the Corps' projects are authorized for multiple purposes, (e.g. flood control, navigation and recreation) and over 60 Corps of Engineer projects include water quality as an authorized project purpose. Flow augmentation for industrial and municipal pollution abatement, acid mine drainage abatement, and other purposes which relate to water quality, are often included in flood control and navigation projects. Water quality management objectives have been developed for each project and incorporated into Corps water control programs wherever possible.

The Corps recognizes that project regulation often plays a significant role in influencing downstream environmental and water quality conditions. Sensitivity to the effects of water control activities on the environment is the cornerstone of the Corps' initiatives for integrating water quality and environmental considerations into water control management.

Experience gained over the last decade, through water control management activities and Corps research and development efforts, has contributed to a growing information base for designing and operating reservoir projects to manage water quality. A large portion of these research efforts were conducted as part of the Environmental and Water Quality Operational Studies Program, an eight year effort which was initiated by identifying technology and information needs for solving environmental problems and meeting the responsibilities of legislative and executive directives.

This work, which was completed in 1985, produced a better understanding of the effects of reservoirs on water and environmental quality. Some of the efforts under this program addressed processes involved in inflow mixing, internal reservoir mixing and suspended solids distribution. Methods for predicting environmental changes and alternatives for managing water and environmental quality were evaluated. Predictive techniques were developed for describing reservoir hydrodynamics, loadings to reservoirs and for determining the ecological effects of reservoir project operation. A variety of other areas were also included in this program, and the resulting technology and criteria has been incorporated into Corps regulations and technical guidance.

In making water control decisions,the Corps must take a variety of factors and often competing demands for the resource into consideration. Where reservoirs are authorized for a single purpose, their operation must be designed to attain this purpose. However, the method of operation can often be flexible and produce benefits over and above the authorized objectives. Operating plans are routinely designed to produce benefits for environmental and social goals such as instream quality, in-lake quality, recreation, power or any other attainable goals that the project can achieve without compromising the authorized project purposes.

The majority of Corps projects are managed for multiple purposes, and more than one goal or objective must be accomodated in project water control plans. Either a single reservoir or a system of reservoirs may be regulated for the multiple authorized purposes, and the potential frequently exists to regulate the project(s) for additional benefits. This flexibility depends on the compatibility of each water use, the characteristics of the project or river system, water use requirements and other factors.

Water levels in impoundments may be regulated to provide sufficient storage space to control floods, as well as to store water for a wide range of uses. Releases may be regulated to achieve requirements for public use, recreation, and to support fish and wildlife needs downstream. System regulation for water quality is most valuable during low flow periods when available water must be used efficiently to avoid degrading lake or river quality. However, even this worthy objective often conflicts with other water needs such as water supply or hydropower storage.

The melding of all of the above considerations usually requires some degree of compromise to achieve water management goals. For each project or system, the use requirements are evaluated to assure the greatest project benefits. This balancing of water use demands, priorities and project capabilities is the overall goal of the Corps water control management program.

Finally, water quality management activities must compete with a large number of other efforts for limited manpower and funding resources. Given a particular level of resources, agencies prioritize their programs, and carry them out at a level of effort consistent with each program priority. The heightened public concern for the environment, and the resulting legislative and executive mandates, have raised the visibility and priority of water quality management programs in the Corps of Engineers which resulted in the accomplishments previously described.

## WATER QUALITY STATUS OF CORPS OF ENGINEERS PROJECTS

### a. Introduction

The Corps of Engineers has constructed and now operates more than 700 water resource projects having a total surface area of nearly 27,000 square kilometers. The geographic distribution of these projects, as depicted in Figure 1, reflects regional differences in water resource development requirements, water control agency responsibilities, and topographic requirements for cost-effective construction. Impoundments providing navigation benefits, which comprise approximately 26 percent of all Corps projects, are located along major inland waterways. These include the Mississippi River and its major tributaries, the Arkansas and Red Rivers draining from the west, and the Ohio and Illinois Rivers draining from the east. Other waterways of importance include the Alabama River and the Tennessee-Tombigbee Waterway in the mid-south, and the Columbia River in the northwest. Twenty one percent of all projects are dry dams or projects which, by design, provide minimal permanent water storage during non-flood periods. These projects are most prevalent in the arid southwest, where flooding conditions are associated with intermittent periods of excessive runoff, and in the New England states.

Reservoir projects providing short- and long-term storage of water, but not navigation benefits, comprise the remaining 53 percent of all Corps projects. These projects can be broadly categorized based on reservoir morphometry and tributary type. Deep, storage reservoirs are formed by the impoundment of higher order streams and rivers, and are frequently located in deep, steeply-sloped river valleys. These projects tend to be deep, narrow and highly dendritic in shape. Mainstem reservoirs are located on lower order (ie. larger) rivers and tend to be shallower, wider, and less complex in shape.

b. <u>Methods</u>

Growing public concern over the quality of freshwater resources and the desire to continue to provide responsible management of the valuable environmental resource provided by its water resource projects led the Corps of Engineers to institute several water resource research programs. The purposes of these research programs were to expand the understanding of processes influencing the environmental quality of reservoirs and tailwaters, and to improve management technologies. As a continuing effort, the Corps has established a number of technology transfer programs as a means of distributing water quality information and technology.

Currently, the Corps is compiling and analyzing water quality information as a means of providing an up-to-date assessment of the water quality status of all its water resource projects. Sources of information include annual water quality reports prepared by District and Division offices, water quality data retrieved from EPA's STORET database system, and detailed evaluations by project management personnel.

For the purposes of this report, portions of the above mentioned information have been reviewed and analyzed. Specifically, this information was obtained through the use of a comprehensive questionnaire designed to solicit detailed information concerning all aspects of project design, operation, and water quality status. The questionnaires were completed by personnel familiar with each project and its water quality characteristics. With regard to water quality status, subjective responses to questions concerning water quality were requested. In general, these responses indicated the presence or absence of water quality problems. In situations where problems were indicated, graded responses allowed assessment of the severity of the problem and the quality of the information upon which the assessment was based. To date, questionnaires for approximately 470 projects have been completed and compiled.

Since questionnaires for all projects have not yet been completed, a sample of questionnaires was randomly drawn and analyzed for the purpose of this report. The sample size was set at 10 percent (46 projects) and samples were drawn from strata based on project type (reservoir, lock and dam, and dry dam) and District. The geographic locations of sampled projects are presented in Figure 2 for comparison with the distribution of all projects (Figure 1). Results presented below are based on these analyses.

c. Assessment

Figures 3 and 4 present the water quality status of tailwaters and pools associated with the sampled projects, respectively. A shortcoming of the data upon which these figures are based is the fact that reliable information concerning water quality status is lacking for approximately 40 to 50 percent of the projects. A number of reasons for this lack of information are possible. The collection, analysis, and reporting of water quality information at many projects is performed by agencies other than the Corps. This is particularly true for projects at which recreation and other water-based resources are managed and maintained by local authorities. Thus, while water quality data may be collected, such data may not be readily available to Corps personnel.

Funding and manpower constraints have a significant impact on the quality and quantity of water quality information collected at many Corps projects. To overcome these constraints, priorities are often established which provide for the collection of appropriate water quality data for those projects at which water quality concerns are deemed to be of highest priority. Other projects, because of historical data or informal knowledge concerning their water quality status, are sampled less intensively or less frequently. Thus, a degree of uncertainty and/or bias exists for data discussed here and extrapolations of data compiled for the sampled projects to all projects are not possible. The data do, however, provide a general assessment of the types of water quality concerns associated with Corps water resource projects and some indication of their relation to other project attributes.

As depicted in Figure 3, approximately 60 to 65 percent of those sampled projects for which evaluations of the water quality status of tailwaters were available were considered not to exhibit problematic conditions. For those projects indicated as exhibiting problematic conditions, several categories of water quality concerns are apparent. Most prevalent are concerns related to flow, the release of waters low in dissolved oxygen concentration, and the erosion and transport of sediment.

Extremes in flow and/or excessive changes in flow, which result from operational procedures required to meet authorized project purposes (e.g., flood control, power generation, etc.), may impact downstream uses. While such conflicts in uses are frequently problematic, every attempt is made to enhance non-authorized benefits without incurring unacceptable impacts on authorized purposes.

Flow-related problems for tailwaters include higher than normal flows following flood events as retained flood waters are released, lower than normal flows during periods then pool storage is being increased, and daily fluctuations resulting from the operation of hydropower facilities, particularly when power is produced to meet peak-load requirements.

The loss of dissolved oxygen in the hypolimnia of reservoirs potentially results in direct and indirect impacts for tailwaters. For projects which, because of their structural or operational characteristics, do not allow for complete reaeration of release waters, dissolved oxygen concentrations below saturation may occur throughout part or all of the summer stratified season. Such is the case for approximately one-third of the projects inventoried here. However, it should be noted only one of the 46 sampled projects experiences periodically severe dissolved oxygen conditions in it's tailwater and that this project is a newly-filled reservoir where such occurrences are predictable and short-lived.

Coincident with the loss of dissolved oxygen from reservoir hypolimnia is the potential for the release of dissolved materials, particularly iron and manganese, from bottom sediments. The accumulation of these materials in reservoir waters, in turn, leads to their potential release to downstream areas. The occurrence of elevated concentrations of metals and nutrients in tailwaters is indicated for approximately 30 to 40 percent of the sampled projects for which such evaluations were made. And, as would be expected, these projects are primarily those for which reduced dissolved oxygen concentrations were reported. It is also important to note that these projects are also reported to receive relatively high inputs of these materials from their surrounding watershed.

The transport of suspended sediment from reservoir to tailwater and/or the erosion and resuspension of bank and bed materials impacts tailwater areas below approximately 40 to 50 percent of the projects for which evaluations were provided. In most cases, impacts are minor and result from increased turbidity. In other cases, degradation of immediate downstream areas is indicated. Preliminary evaluation of information suggests that, while project operation plays a significant role in the determination of release conditions, pronounced regional patterns in the distribution of such conditions are apparent. In general, reservoirs located in regions dominated by highly-erodible soils experience higher inputs of suspended sediment and, therefore, often release turbid waters.

An evaluation of water quality conditions in pools, also based on sampled responses to the questionnaire, are presented in Figure 4. Most prevalent were problems related to the eutrophication process. These include excessive nutrient concentrations, algal blooms, reduced water clarity, macrophyte infestations, and the loss of dissolved oxygen in bottom waters. Other conditions of concern include excessive concentrations of reduced iron and manganese in bottom waters, and the accumulation of sediment and contaminants. As was discussed for tailwaters, problematic conditions were indentified for approximately 40 to 50 percent of the pools for which evaluations were available. And, again, varying degrees of severity in problematic conditions are apparent.

Complex interactions between biotic and abiotic components of the reservoir ecosystem make simple, meaningful evaluations of data difficult; however, several general patterns emerge from existing information. Most notable is the impact of watershed processes and the transport of material from watershed to reservoir. The loss of nutrients and sediment from watersheds and their accumulation in reservoirs fosters the growth of aquatic plants, primarily algae, and losses in storage volume. These effects, in turn, lead to reduced water clarity, reduced dissolved oxygen concentrations in bottom waters, and the potential for internal material cycling between nutrient-rich sediments and the overlying water column.

An understanding of the linkage between watershed and reservoir is critical to our understanding of water quality processes and the control of water quality problems. This is of particular concern to agencies such as the Corps of Engineers since primary control of water quality conditions must target processes occurring in that portion of the reservoir-watershed ecosystem in which the water control agency has little or no regulatory authority. As an indication of the potential importance of watershed processes, it should be noted that watershed-area to lake-area ratios are higher for reservoirs than for natural lakes. Obviously, as this ratio increases, so does the potential for increased or excessive material loads to the reservoir.

A review of landuse patterns in the watersheds of the sampled reservoir projects indicates that, on the average, natural, agricultural, and urban/residential areas account for 45, 45, and 10 percent of the landuses in the reservoir watersheds, respectively. Since agricultural and urban/residential areas often contribute excessive nutrient and sediment loads to streams and rivers, the control of point and nonpoint sources are clearly indicated as the primary means by which reservoir water quality can be protected or improved through reduced loading. This is underscored by the observation that sampled projects for which eutrophication-related problems were indicated also receive nutrient loads deemed by reservoir water quality personnel to be excessive and problematic.

## FUTURE DIRECTION

The following are areas where additional emphasis would benefit both Congress and the federal water resource agencies in understanding and managing water quality at federal reservoir projects.

a. Extensive research has been conducted to develop improved techniques for analyzing river and reservoir water quality dynamics, reservoir and reservoir system operations and associated interrelationships. However, many unknowns and problems remain. Agency water quality related research programs will be prioritized to address urgent needs.

b. Applications of technologies to ameliorate water quality conditions at reservoirs have been undertaken by the Corps of Engineers. Varying degrees of success have been achieved, and it has become evident that additional direct field application and evaluation of water quality enhancement techniques is needed to fill the void between research and successful use in the field. The Corps intends to continue to conduct demonstration programs to improve design guidance and define limitations, capabilities and ancillary effects. Interagency cooperation in this program would extend the limits of applicability and facilitate sharing of agency expertise. This effort, in concert with the previously outlined initiatives, would greatly enhance the federal agencies' abilities to carry out Congressionally mandated responsibilities pertaining to reservoir water quality management and the achievement of national water quality goals.

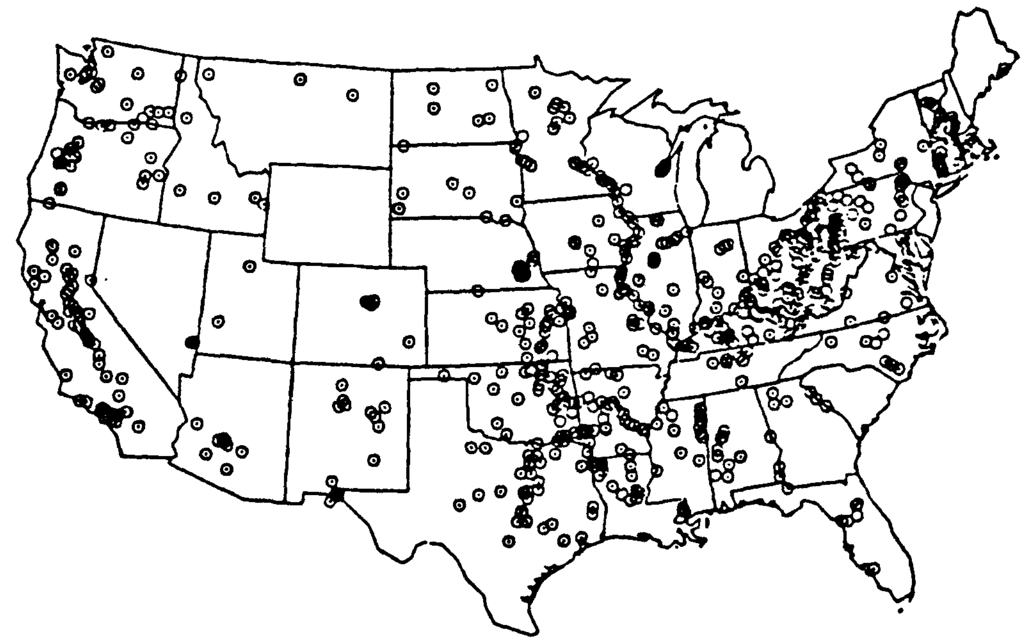


Figure 1. Geographic distribution of Corps of Engineers water resource projects.

Figure 2. Geographic distribution of a ten percent, stratified, random sample of Corps of Engineers projects for which questionnaires have been received.

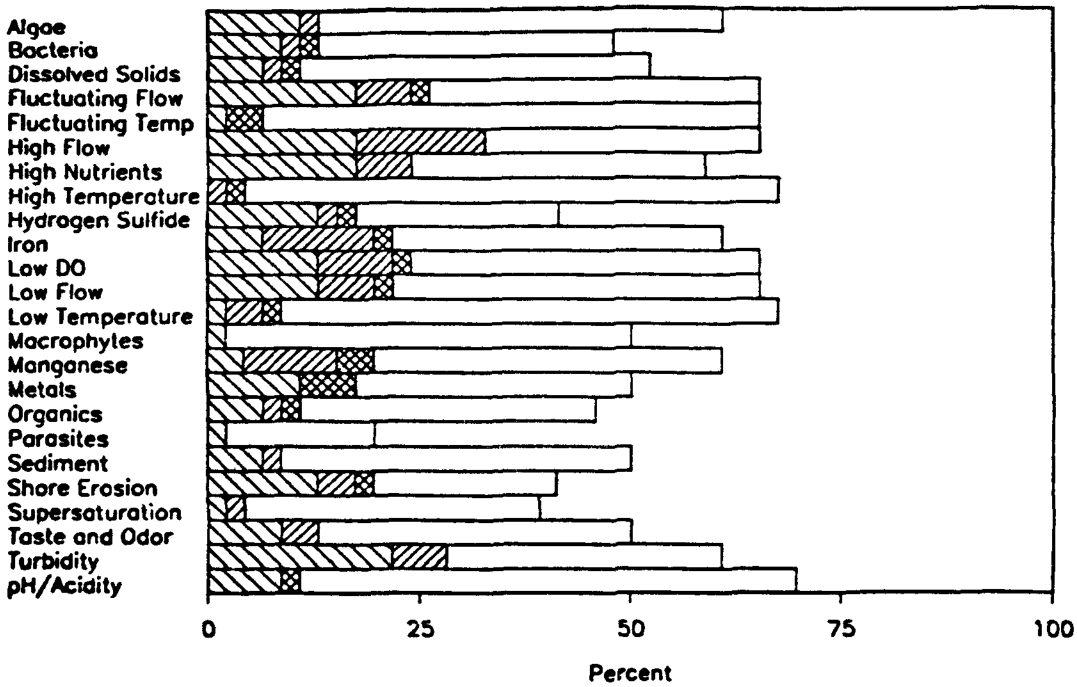



Figure 3. Frequency of occurrence of occasionally problematic (coarse hatching), intermittently problematic (fine hatching), chronically problematic (cross hatching), and non-problematic (no hatching) water quality conditions in tailwaters. Difference between accumulative frequency and 100 percent indicates percentage of projects for which no evaluation was made.

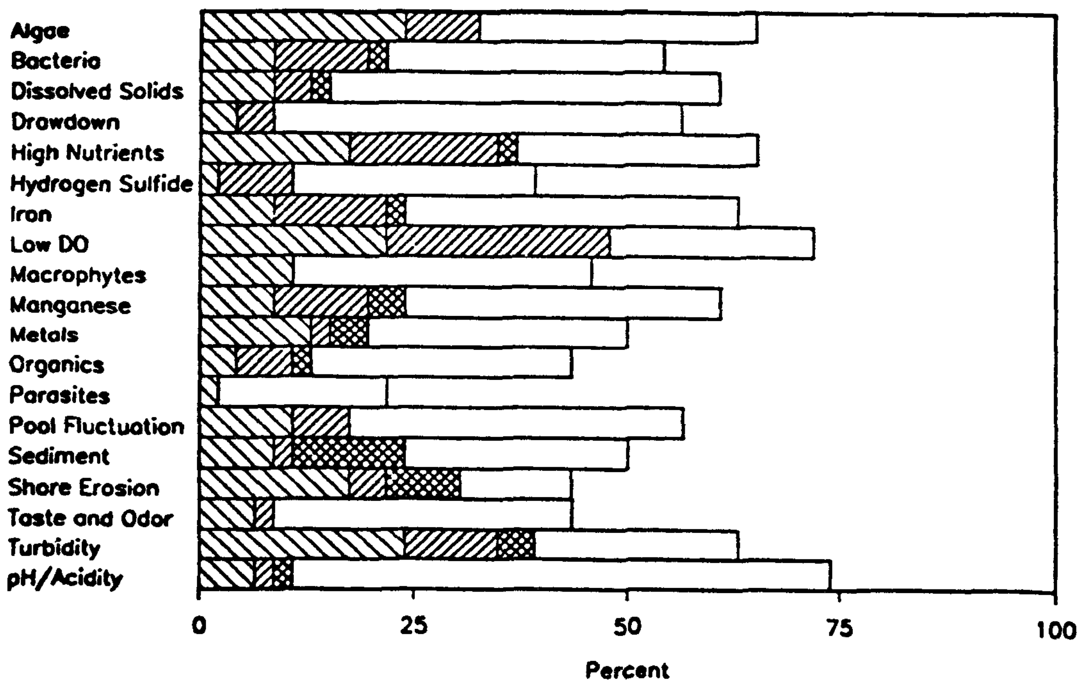



Figure 4. Frequency of occurrence of occasionally problematic (coarse hatching), intermittently problematic (fine hatching), chronically problematic (cross hatching), and non-problematic (no hatching) pool water quality conditions. Difference between accumulative frequency and 100 percent indicates percentage of projects for which no evaluation was made.

# APPENDIX G
# TENNESSEE VALLEY AUTHORITY'S ASSESSMENT SUPPLEMENT

## INTRODUCTION

This chapter provides an assessment of water quality conditions in the Tennessee Valley Authority's (TVA) system of multipurpose water resource projects (Figure 1). It responds to the Environmental Protection Agency's (EPA) request for information for its report entitled "Dam Water Quality Study--A Report to Congress under Section 524, Clean Water Act of 1987." It is organized in three main sections: Assessment of Water Quality; Policies - Water Quality Management; and Recommendations.

## ASSESSMENT OF WATER QUALITY

Water quality conditions for reservoirs in the Tennessee Valley were assessed using the approach applied by the Corps of Engineers to assess its 783 projects. First, a questionnaire was completed for each reservoir by an individual knowledgeable about water quality in the reservoir. Then information was obtained from personnel familiar with the primary reservoir uses and reservoir operations. Finally, in several group settings, the questionnaire responses were reviewed for uniformity in defining the parameters and rating each project. Thirty-three projects were assessed, including all the hydropower projects and four nonhydroprojects. Those projects not included are small projects for which no data were available.

The results are presented in Figures 2 and 3 for pools and tailwaters, respectively. Definitions are as follows: "continuous:" a chronic or continuous problem; "seasonal:" an intermittent problem occurring on a seasonal basis; "infrequent:" an occassional problem ocurring infrequently on an annual basis; "no problem" and "no data:" self-defined; "severe:" a severe impact resulting in the long-term loss of one or more user benefits; "significant:" a significant impact that restricts but does not eliminate user benefits; "minor:" a minor impact which does not restrict user benefits.

Water uses were severely impacted at several sites. Low DO, hydrogen sulfide, iron, and manganese are considered to be at sufficient levels that the fishery at Upper Bear Creek Reservoir is practically nonexistent. Other reservoir projects having severe use impairment are the three Ocoee projects where sediment accumulation, iron, manganese, turbidity, and metal contaminants are adversely impacting aquatic life and recreation, primarily in Ocoee number 3 with less impairment in Numbers 2 and 1. Finally, the Nolichucky Reservoir has been filled with sediment to the point that it is no longer considered a reservoir.

The results indicate that in reservoir pools the most significant impacts were pool level fluctuations and bacteria (about 50 and 30 percent of the reservoirs, respectively). The next most significant user impacts were turbidity, algae, macrophytes, sediment accumulation, and shore erosion, all of which occur at 15-20 percent of the reservoir projects. Minor impacts, occurring at 20 percent or more of the reservoir projects, were related to the following parameters; iron, manganese, low DO, turbidity, low temperature, high nutrients and algae, macrophytes, sediment accumulation, pool level fluctuation, shore erosion, pH/acidity, bacteria, and fish parasites.

Several items worth noting for the analysis on pools are: (1) data on hydrogen sulfide were limited and the results of this analysis may change when more data becomes available; (2) several parameters had high rates of recurrence with the potential to impact uses in the future: i.e., high nutrients, sediment accumulation, shore erosion; (3) low DO seasonally occurred in about 70 percent of the reservoirs, but user impacts were considered minor becasue the condition was restricted to the hypolimnion or bottom waters of the reservoir, in which case "no data" was designated; and (4) more data are needed on organics and metals in fish flesh.

For reservoir tailwaters, the results indicate that the most significant impacts resulted from low DO, streamflow (high, low, and fluctuating), and low temperature. The next most frequent user impacts were associated with iron, manganese, hydrogen sulfide, turbidity, metal contaminants, streambank erosion, bacteria, and fish parasites. All of these parameters occurred at about 15-20 percent of the projects. The most frequent minor impacts, occurring at 20 percent or more of the projects, were related to the following parameters: low DO, turbidity, high flow, fluctuating flow, low temperature, high temperature, fluctuating temperature, streambank erosion, and parasites in fish.

Several items worth noting on the tailwater assessment are: (1) even though data were not available on the user impacts of gas supersaturation, the impacts are probably minor; and (2) more data are needed on hydrogen sulfide, bacteria, and fish flesh contaminants.

## Reservoir Water Quality Management

TVA's programs on reservoir water quality management are focused on three areas: tailwater management, reservoir management, and watershed management. The long-range strategy is to achieve proper management of all TVA reservoirs and tailwaters; however, at present the activities have been directed toward reservoirs and tailwaters that have the greatest user impacts.

TVA actively pursues reservoir water quality management through the formation of "partnerships". To the extent practical, joint projects are conducted with State agencies, EPA, and with public interest groups. These partnerships are invaluable in ensuring that appropriate analyses are conducted so that results are implemented in a timely manner. The partnerships also reduce TVA costs for conducting studies and implementing solutions to priority problems.

Tailwater Management Strategy--TVA's tailwater management strategy concentrates on improving the habitat for fish and aquatic life, recreational floating, assimilative capacity for treated wastewaters, and providing for municipal and industrial water supply. The typical water quality parameters include DO, streamflow, temperature, iron, manganese, hydrogen sulfide, pathogens, sediment, and total dissolved gases.

At the present time TVA is concentrating its efforts on improving DO concentrations and enhancing stream flows. Elements of this effort include:

1. Assessment of existing water quality, biological conditions, and potential uses of the tailwater, followed by a plan that identifies needed improvements and a monitoring strategy to assess its effectiveness.

2. Aeration and/or oxygenation of the hydropower releases to about 4mg/L during those portions of the year when DO fails to meet this value.

3. Provision of minimum or increased flows downstream from hydroelectric power plants, tailored to meet specific needs as determined through field studies and data analyses.

4. Investigation of impacts from iron, manganese, and hydrogen sulfide and evaluation of methods to reduce these substances within the reservoir as well as the tailwater.

The chapter on case studies provides more information on the activities at the Norris and Upper Bear Creek projects.

<u>Reservoir Management Strategy</u>--TVA's reservoir management strategy is directed toward achieving objectives for fish and aquatic life, recreation (primarily boating and swimming), assimilative capacity for treated wastewaters, and municipal and industrial water supplies. The water quality parameters that are addressed include DO, temperature, iron, manganese, hydrogen sulfide, pathogens, sediment, turbidity, nutrients, algal concentrations, toxic substances, and aquatic weed growths.

TVA develops water quality management plans for selected reservoirs where water uses are suspected of being affected and significant interest is expressed by state agencies, EPA, and the public and private sectors. Compared with free-flowing streams, reservoirs are very complex water bodies that are affected not only by the retention of the water behind the dam, but by operational procedures for the dam and environmental processes that occur within the water body itself.

Because a number of agencies and water users have various authorities and responsibilities associated with reservoirs, joint efforts are pursued to achieve objectives and maximize the benefits of the reservoirs. The following are the elements that are included in TVA's reservoir water quality management plans:

1. An issues analysis is performed to define reservoir uses and objectives, and key issues.

2. A task force is organized for the reservoir that includes State and Federal agencies, universities, lake users, municipalities, and industry, as appropriate.

3. Data is collected and analyzed to address key issues and explore management alternatives.

4. A plan is developed with recommended actions, including additional data/analysis needs, point and nonpoint source actions, in-reservoir enhancement methods, water quality improvement demonstrations, and citizen involvement.

5. Activities committed to by TVA are implemented.

6. Follow-through actions are reevaluated to determine their effectiveness in achieving objectives.

Reservoir management plans have been developed and are being implemented at 5 projects. Special reservoir studies are also being conducted for other reservoir projects where issues with limited scope need to be addressed. More information is provided in the chapter on case studies for the Boone and Guntersville projects.

Watershed Management Strategy--TVA's watershed management strategy is primarily directed toward the reduction of nonpoint sources of pollution from agriculture, abandoned mines, urban runoff, and land development activities. The objective is to improve water quality conditions in streams as well as reservoirs and tailwaters. Parameters of interest include nutrients, toxic substances, sediment, pathogens, ammonia, and carbonaceous biochemical oxygen demand. TVA's efforts in watersheds are directed towards demonstrating nonpoint source management solutions and encouraging full-scale implementation actions by other agencies and private landowners. Even though reservoirs are the ultimate recipients of nonpoint source contamination from the watershed, cause/effect relationships between contaminants from watersheds and water quality in reservoirs are poorly defined.

The elements of TVA's watershed management strategy are as follows:

1. Pertinent information is gathered from all available sources and issues that need to be addressed are identified.

2. An aerial inventory of nonpoint sources is made.

3. A "delivery analysis" is conducted in which parameters from contaminant sources to point of reservoir inflow are noted.

4. Water quality and aquatic life (e.g., index of biotic integrity) are monitored at selected points to better define issues and assess trends.

5. Nonpoint source control demonstrations are conducted and successful technology is transferred to appropriale agencies and individuals.

6. Institutional arrangements are developed for full-scale implementation of priority point and nonpoint source controls.

## POLICIES - WATER QUALITY MANAGEMENT

The TVA system of multipurpose dams with its more than 11,000 miles of shoreline and 600,000 acres of water was largely completed by the late 1950s. With the completion of the dam construction program, TVA has turned its attention to managing the reservoir system and promoting the proper growth, conservation, and management of the Agency's natural resources. As part of this continuing effort, the TVA Board of Directors authorized in September 1987 the broadest reassessment in 50 years of the operating policies of its dams and reservoirs. The central issues being addressed by the study are whether water quality and recreation should be added as primary purposes of TVA reservoir operations to the statutory purposes of navigation, flood control and electrical generation. The study is being conducted in accordance with the procedures of the National Environmental Policy Act and will determine the long-term policies that should direct TVA efforts in reservoir system operations and river management into the next century. The current schedule calls for presentation of the final report and Environmental Impact Statement and the results of public review and comment of the recommendations in 1989.

### Water Quality Policies, Codes, and Instructions

TVA has adopted the following operational policies or codes related to water quality. The most comprehensive policy is contained in TVA Code IX ENVIRONMENTAL QUALITY. This code states that:

> TVA will ensure that its programs, projects, and activities protect and enhance the quality of the human environment, including the air, water, and land resources of the TVA region and other areas impacted by its operations through compliance with applicable Federal, State, and local laws and related regulations and through the implementation of more rigorous controls or practices where practical, beneficial, and cost effective.
>
> TVA's planning procedures provide for early involvement of appropriate governmental agencies and the public in decisionmaking related to activities which significantly affect the quality of the environment. In addition, TVA prepares reports on the status of environmental quality in the Tennessee Valley.

The code further states that:

> implementation of this policy is a basic management responsibility and TVA expects all line managers to provide positive environmental leadership in carrying out agency operations and activities. TVA conducts monitoring and auditing activities to measure and evaluate the extent to which environmental quality standards and commitments are met.

TVA's specific policy on water quality is contained in TVA Code IX WATER QUALITY MANAGEMENT. This code states that:

> TVA's water quality management activities have as their primary purpose the restoration or maintenance of suitable water quality throughout the Valley to permit optimum use of surface and ground waters for municipal, industrial, and agricultural water supplies; for propagation of fish and wildlife; for aesthetic enjoyment; for water-contact recreation; and for future development of streams and reservoirs in the public interest. The goal is to keep all waters clean and free of pollutants......It applies existing or, where none exist, develops water quality criteria for use in its water resource development projects; where there is no practical alternative to disposal of hydrowastes into streams, it encourages the imposition of regulatory controls designed to obtain the highest degree of waste treatment available under existing technology, within reasonable economic limits, to protect the Valley's surface and groundwater resources.

TVA's policy also recognizes that:

> its statutory program of impoundment and streamflow regulation produces significant changes in streamflow and in the physical, chemical, and biological characteristics of affected waters in the Valley. Overall, these alterations are highly beneficial, but some changes have adverse water quality effects and may reduce the capacity of the streams to assimilate wastes. TVA conducts studies and field investigations to identify and evaluate the interrelationship of water resource development and water quality, utilizing research findings of other agencies and institutions to the maximum extent feasible. Consistent with the primary purposes for which TVA projects are operated under the TVA Act, TVA operates its system of reservoirs to minimize adverse water quality effects and to give due account to State-designated downstream uses. TVA controls or treats wastes from its own operations in accordance with the stated primary purpose of this policy, cooperating with Federal and State pollution control agencies. In the administration and disposal of TVA lands and in the licensing or regulation of water-use facilities constructed on TVA reservoirs, TVA incorporates pollution control provisions, including requirements for using best management practices to control nonpoint-source pollutants, in deeds, leases, licenses, permits, and other documents as appropriate.

In addition to these policies, water quality considerations are also included in TVA Code IX FLOODPLAIN MANAGEMENT AND PROTECTION OF WETLANDS, TVA Code IX STREAM MODIFICATION, and TVA Code XII RESERVOIR OPERATION. Of particular interest to this study is the policy which specifies how TVA regulates reservoir levels and streamflow (where consistent with statutory purposes) to:

- Minimize detrimental water pollution effects and produce water quality benefits for the public health and public use of the reservoirs, such regulation to be provided without accepting liability for the regulation and without relieving the polluter from full responsibility for such pollution.

- Make the greatest possible contribution to the sustained control of hazards to health in the Tennessee Valley region and to maintain standards for control of mosquitos which are fully as effective as those required for privately owned river impoundments under prevailing public health regulations.

- Enhance fisheries management and other recreation uses of these waters. Under these conditions, it attempts to provide pool levels favorable for recreational uses and to minimize fluctuations during the prime recreation season and spawning season on tributary reservoirs. Also, wherever primary operating requirements permit, it attempts to regulate sufficient discharges from dams to provide for boating and fishing activities on certain streams.

- Minimize possible adverse effects on propagation of fish life and enhance the value of Valley fisheries.

- Provide a water supply for domestic, industrial, or agricultural uses.

- Accommodate individual navigators, ferry operators, farmers on river islands and shore lands, and others who may otherwise suffer discomforts of inconveniences or may need special flow regimes to accommodate short-term scientific research or management demonstrations. Such regulation does not entail acceptance of responsibility for serving such incidental comforts or conveniences or infringe on TVA's acquired right to flood the reservoir margins whenever or wherever required for the major purposes of this program without regard to any secondary land use which may have been undertaken subject to such flowage rights.

## RECOMMENDATIONS

As TVA reported to the U.S. Senate's Subcommittee on Environmental Pollution in 1985, 7 of the 10 most critical water quality problems in the Tennessee Valley are related to nonpoint pollution. TVA said then and still believes nonpoint pollutants are not being adequately addressed, and the Clean Water Act goals of "fishable, swimmable" waters will not be met in many parts of the Valley unless additional point and nonpoint pollution control measures are implemented. Damage is not only occurring to natural resources but public health, economic development efforts, water supplies, and the Nation's $1.53 billion investment in the TVA reservoir system are affected.

Both in the region and nationally, there is increasing public recognition of the interrelationships between land-based activities, surface water pollution, and groundwater contamination. Many of the most intractable environmental challenges currently facing the nation involve impacts that involve two or more of these areas. The major constraints to addressing these problems are limited resources and the difficulties inherent in dealing with multimedia impacts through existing medium-specific programs. Recent legislation offers some encouragement. The conservation title of the Food Security Act of 1985 established major national programs (Conservation Reserve, sodbuster, swampbuster) that concurrently address questions about agricultural overproduction, soil erosion, and wetlands destruction. The Water Quality Act of 1987 provides States with new and more broadly based incentives to define and address the nonpoint pollution issues that chronically impede attainment of the goals of the Clean Water Act. Substantial funding is authorized for both these initiatives. Neither can be expected to yield instantaneous cures for the longstanding national and regional issues that they address. Both, however, offer hope for major improvements over the long term if resources are allocated to implement these programs.

EPA maintains it has sufficient authority and responsibility to oversee the preparation and implementation of measures to improve water quality nationally. TVA supports EPA and the States' efforts to use their authority and to make available the resources necessary to address water quality problems. Our experience with water quality in TVA's reservoir system indicates that no major improvement will occur until point and nonpoint source controls are considered and implemented as part of the overall water quality improvement strategy. To do this in the most cost effective way, innovative approaches may be necessary, such as allowing States to use more of their allocation of the existing $2.4 billion construction grants or revolving loan program to fund cost-effective nonpoint pollution control projects. In recent studies with EPA and the State of Tennessee, TVA has found that innovative solutions can be more cost-effective than building traditional advanced wastewater treatment plants. If the Tennessee Valley and the Nation are to achieve Clean Water Act goals, the States should be provided with the flexibility to make tradeoffs in point versus nonpoint abatement, once secondary treatment requirements are met, and in targeting clean water funding to where it is most cost-effective.

As questions arise with regards to eutrophication, toxics, and sediment buildup in streams and reservoirs, it becomes more apparent that water resource interests need to take a more active role in the triennial review of State water quality standards. Areas of particular interest include:

1. Stream Use Classification--TVA believes that lake and reservoir water quality can be managed better if a distinction is made between free-flowing streams, lakes, impoundments, and tailwaters. TVA has offered to work with the States and EPA in developing criteria and standards for impounded waters and tailwaters that recognize the hydrologic and related physical, chemical, and biological differences between these water bodies.

2. Impaired Waters Designation(s)--Additional measures are needed to control pollutants that are causing cultural eutrophication, toxics impacts, and sediment buildup in streams and reservoirs. Water bodies with particular use impairments should be identified categorically as impaired waters, e.g., "Nutrient Sensitive Waters", "Erosion Sensitive Watershed." Following this designation, watershed or areawide pollutant control programs should be developed that emphasize the control or treatment of point and nonpoint source contributions.

Taken together these policy issues strongly suggest the need to reexamine resource management and pollution control strategies. Better integration of these programs has not only become an important policy issue in the Tennessee Valley, but nationally as originally recognized by the Water Resource Council (WRC) in its "Second National Water Assessment," 10 years ago.

## Water Quality Research Recommendations

Additional activities beyond those now carried out by the Federal government are needed to adequately address water quality concerns. The following are critical research needs that have been identified by TVA's environmental engineers and scientists.

Water Quality Criteria--Existing criteria and standards are essentially based on "fixed" concentrations for a single constituent. For example, EPA's dissolved oxygen (DO) criteria document has progressed from recommended minimum concentrations for selected levels of protection to the point where they consider the type of resource to be protected, i.e., whether it is a warm or cold water fishery, life stage of the fishery resource and substratum or habitat condition. This is a significant improvement, but the criterion remains a single stream value and thus fails to fully address the needs of resource managers. In highly regulated rivers like those managed by Federal water resource agencies, water quality criteria and standards are needed that take into consideration (1) the interaction between multiple constituents, (2) the rate of change that could result in unacceptable environmental conditions, and (3) the frequency and duration of exposure of target organisms.

Total Dissolved Gases (TDG)--TDG is another issue deserving attention because they have been observed at relatively high concentrations during flood control operations at dams on the Tennessee River and elsewhere. However, the effects on downstream fisheries have not been adequately assessed to determine if these elevated concentrations are significant.

Hydrogen Sulfide--Hydrogen sulfide is being detected in the releases from water resource projects. This constituent is extremely toxic at very low concentrations (i.e., 2 μg/l). Limited information is available on the occurrence of hydrogen sulfide in reservoir releases because present analytical methods are not sufficient to detect toxic levels. Information about the rate of oxidation of hydrogen sulfide is also limited, but it can vary considerably because of naturally occurring catalysts that result in rapid oxidation; however, in the absence of such catalysts, hydrogen sulfide can persist downstream for several miles before it is oxidized to a nontoxic state. Hence, additional field data are needed on the occurrence and persistence of hydrogen sulfide.

Temperature--The releases from some reservoir projects can contain water that is too cold for desirable fish growth in the downstream tailwater, and in some cases spawning activities can be significantly affected by temperatures in the reservoir releases. Work at the Bureau of Reclamation's Flaming Gorge project has demonstrated one method for improving temperatures. However, less expensive means may be available.

For example, surface water pumps may be feasible to mix the upper layers that have warmer temperatures with the colder layers in such a way that these two water sources are blended before being released through low-level outlets.

Minimum Flows--There are two key issues related to the provision of minimum streamflows below hydropower projects: (1) the quantity of flow required to achieve fishery and aquatic life objectives and (2) the means of providing such minimum flows, i.e., the use of "continuous" flows versus the use of "pulsing" flows that are more desirable from a hydropower viewpoint. Concerning the first issue, there is a need to better predict the effects of various streamflow levels on aquatic life. There are several available methods for predicting the effects of flow quantity on aquatic life, but their accuracy is suspect. In addition, because recreationists are the most immediate beneficiaries of tailwater improvements, better methods are needed to determine from their viewpoint which flows are desirable.

## Reservoir Research Recommendations

Reservoir Models--Even though significant progress has been made in developing methods for analyzing reservoir water quality, new mathematical modelling methods in two dimensions have been applied to only a few reservoirs. Additional application of such models is critically needed to more fully understand the water quality changes that occur within a reservoir. Stream models have been in existence since the 1920s, and estuary models have been available since about 1970, whereas 2-D reservoir water quality models have only become available during the 1980s. These models have significantly improved the ability to assess and predict such things as DO and the mechanisms that consume oxygen within the reservoir; however, even with recent developments with the 2-D model, the effects of inflow water quality on reservoirs has still not been clearly defined. There is a need to identify the reservoir water quality effects of various sources of contamination within watersheds, particularly nutrients from point and nonpoint sources. The direct linkages between these sources of contaminants and effects on overall water quality in receiving impoundments have not yet been defined quantiatively . Sound assessments of the mechanisms that affect water quality within reservoirs are also needed to determine the effects of changes resulting from reservoir operations. For example, in the TVA system, consideration is being given to maintaining summer pool levels through the end of October each year, and sufficient modeling has not been conducted to predict any resultant changes in water quality. Modeling is also needed to predict water quality in large embayments to reservoirs. From a biological standpoint, embayments are extremely important, yet these bodies of water are not usually considered in reservoir models.

Hypolimnion Water Quality--If any resultant flow through a project is substantially reduced for a portion of the year, it is not possible at this time to predict the effects on existing uses. Water quality issues such as low DO in the hypolimnion can result and, in turn, contribute to the potential release of hydrogen sulfide as well as manganese from the sediments.

## Technology Development Recommendations

Aerating Turbines--Considerable research and development activities have been initiated on various methods to increase water quality in hydropower releases. Several of these methods have been evaluated over the past five years on full-scale operations. However, most of them are retrofit technologies. There is a national need to develop new designs for turbine replacement wheels in the next decade. The objective would be to incorporate aeration capabilities in the turbine system in such a manner that minimum impacts would occur to power generation as well as operations. A large number of existing turbines in the United States will be replaced over the next two decades; therefore, this proposal offers a significant opportunity to enhance the dissolved oxygen concentrations in turbine releases nationally.

Habitat Modifications--Habitat modifications within tailwaters could be a less costly alternative to present minimum flow strategies. Such modifications would be one-time expense items as opposed to annual operational expense items. This concept can also be extended to certain areas within reservoirs. It is believed that some water uses can be significantly enhanced by improving localized areas of the reservoirs. One example is the embayment enhancement option. Another example is the provision of refuges for fish that may require the higher dissolved oxygen levels found in cool waters, e.g., a submerged reservoir can be constructed within a reservoir to contain high-density cold water and provide habitat for striped bass.

## Operational Monitoring Recommendations

Reservoirs with long retention times and low nutrient levels can develop low dissolved oxygen concentrations in the hypolimnion, triggering the release of hydrogen sulfide, iron, and manganese. In some cases, such occurrences may be avoided by changes in outlet levels or release patterns. In other cases, they may be aggravated by changes in release patterns that result from reservoir operations for other purposes, e.g., raising pool levels for longer durations during the recreation season can cause some significant changes in reservoir release patterns. Water quality within reservoirs may be affected by changes in watersheds and year-to-year variation in hydrology in the form of annual rainfall/runoff. All of these interactions are complex and changes in the water quality of the reservoir cannot simply be attributed to one factor. Therefore, it is necessary to conduct appropriate monitoring and to determine the cause-and-effect relationships for processes within reservoirs. Mathematical models calibrated to field data offer one of the best tools for exploring reservoir operations and evaluating management alternatives. Reservoirs are much more complex than free-flowing streams, resulting in three-dimensional variations in water quality as opposed to single-dimensional.

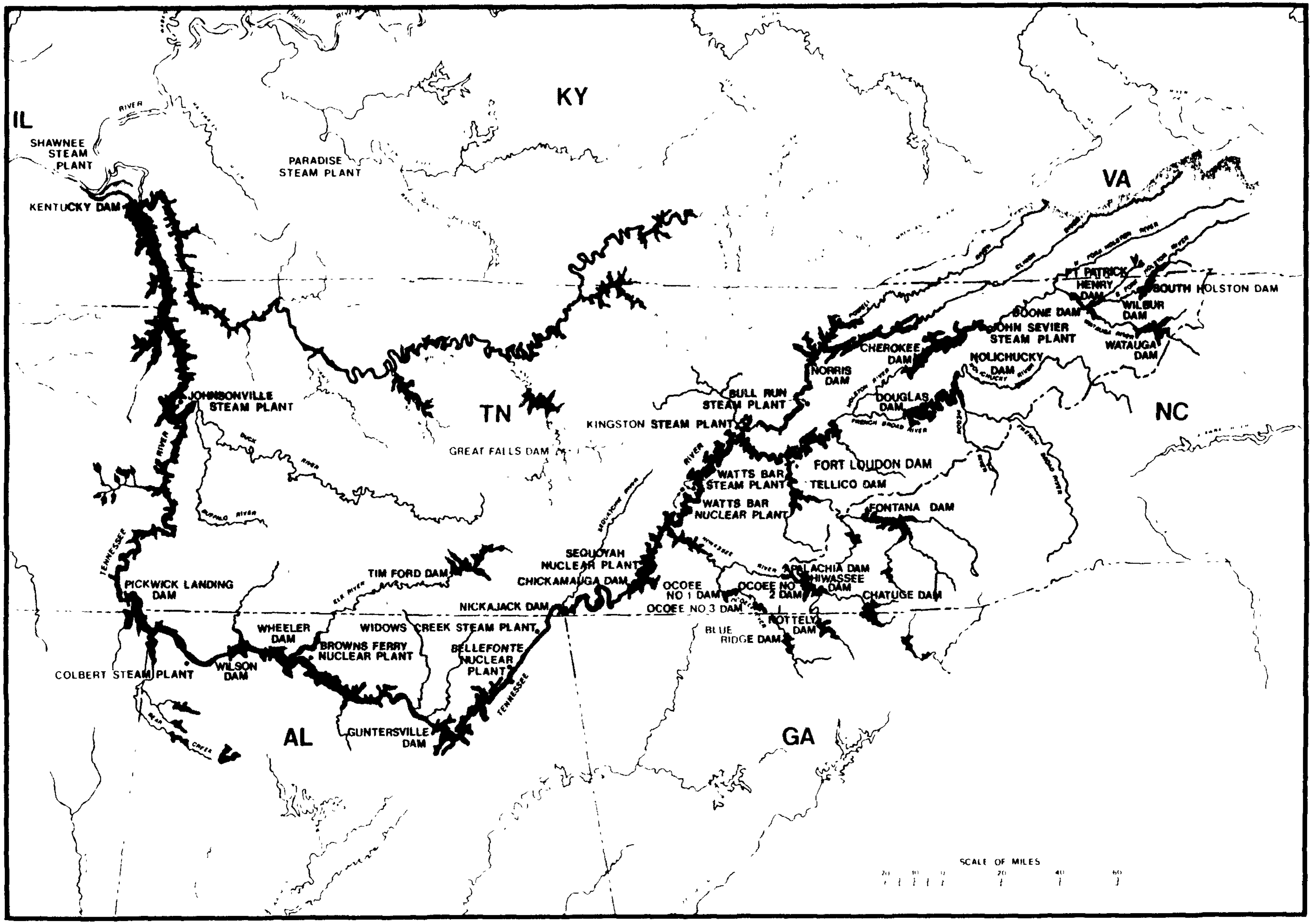
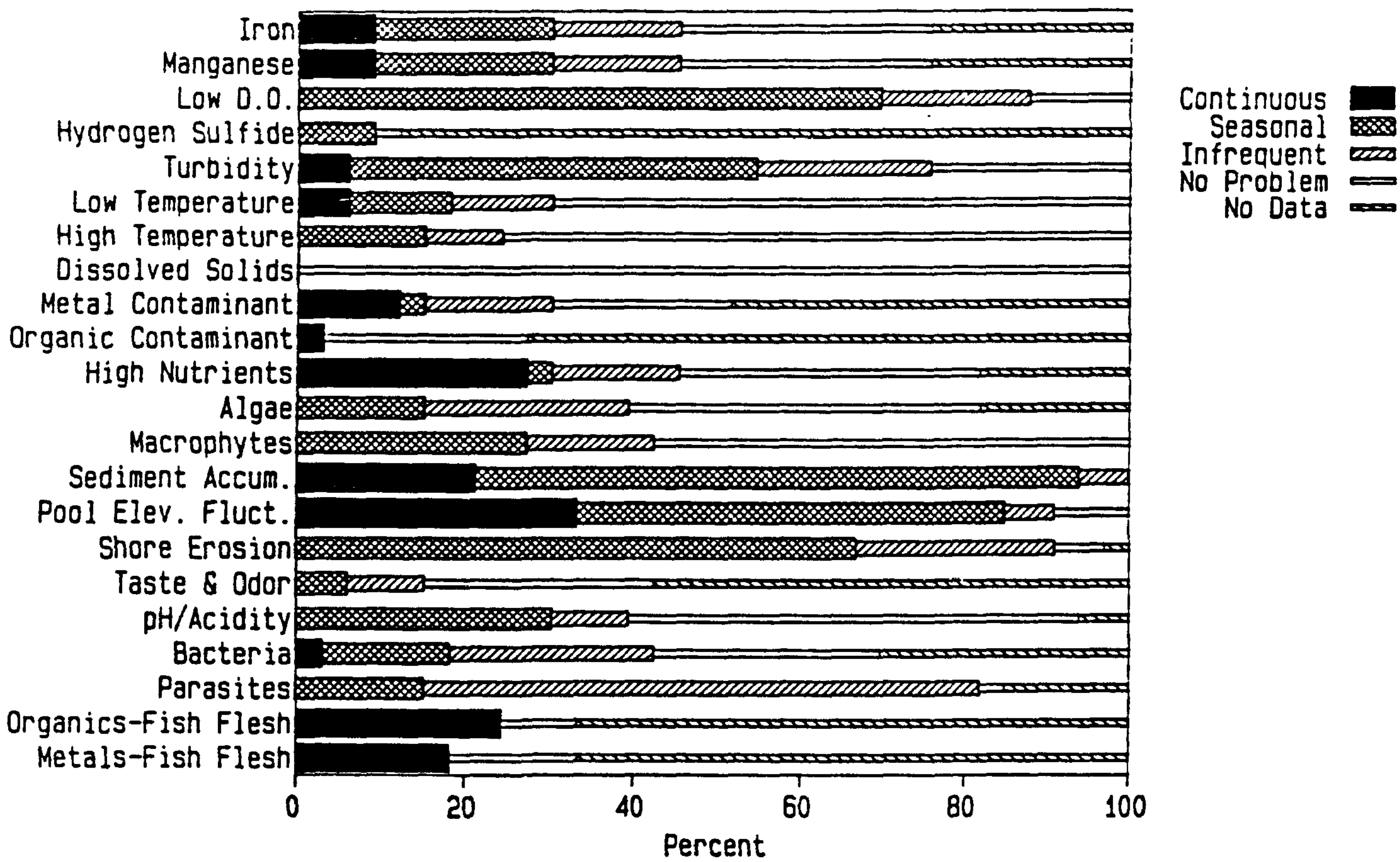



Figure 1. The Tennessee Valley Authority's multipurpose water resource system.



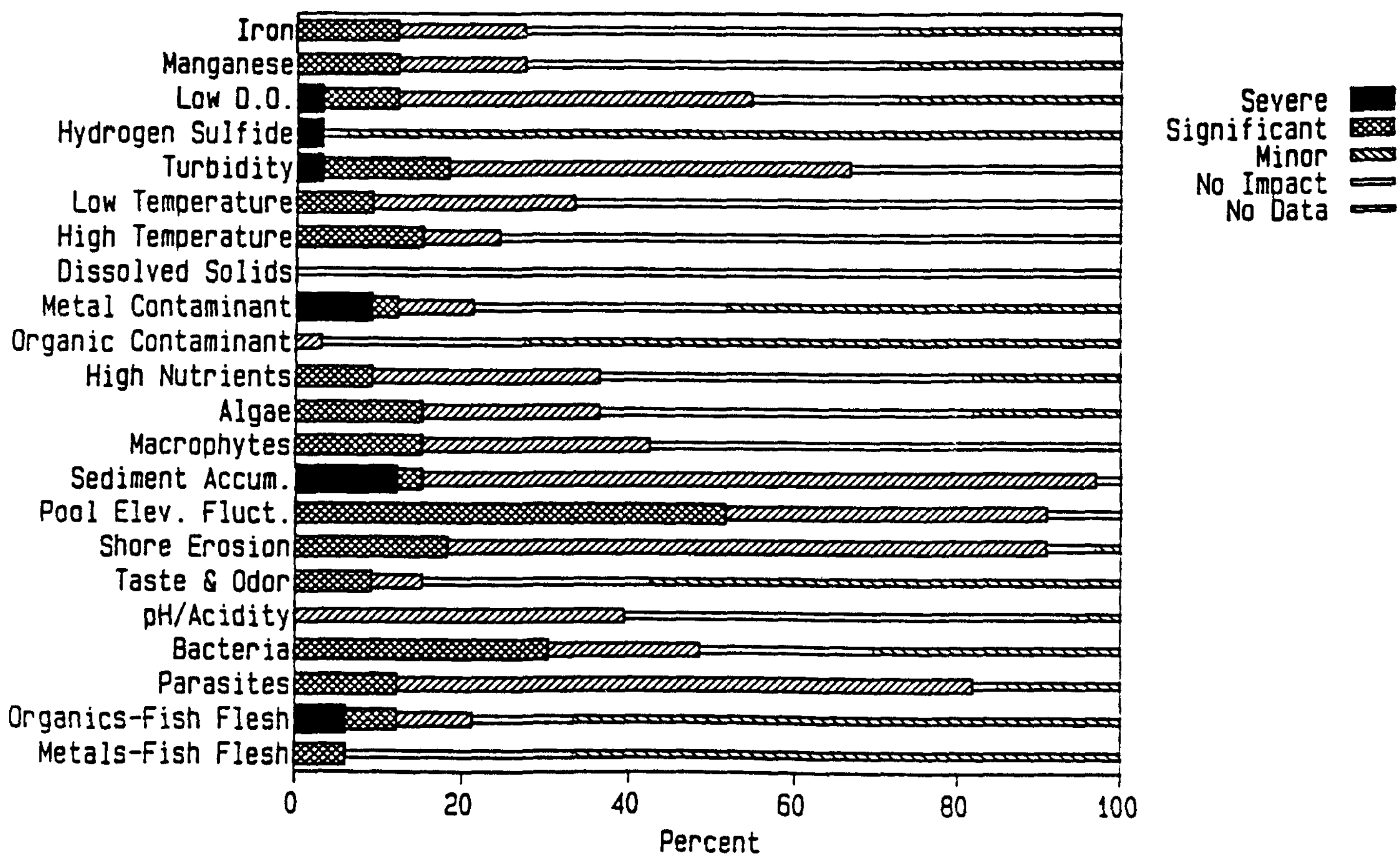
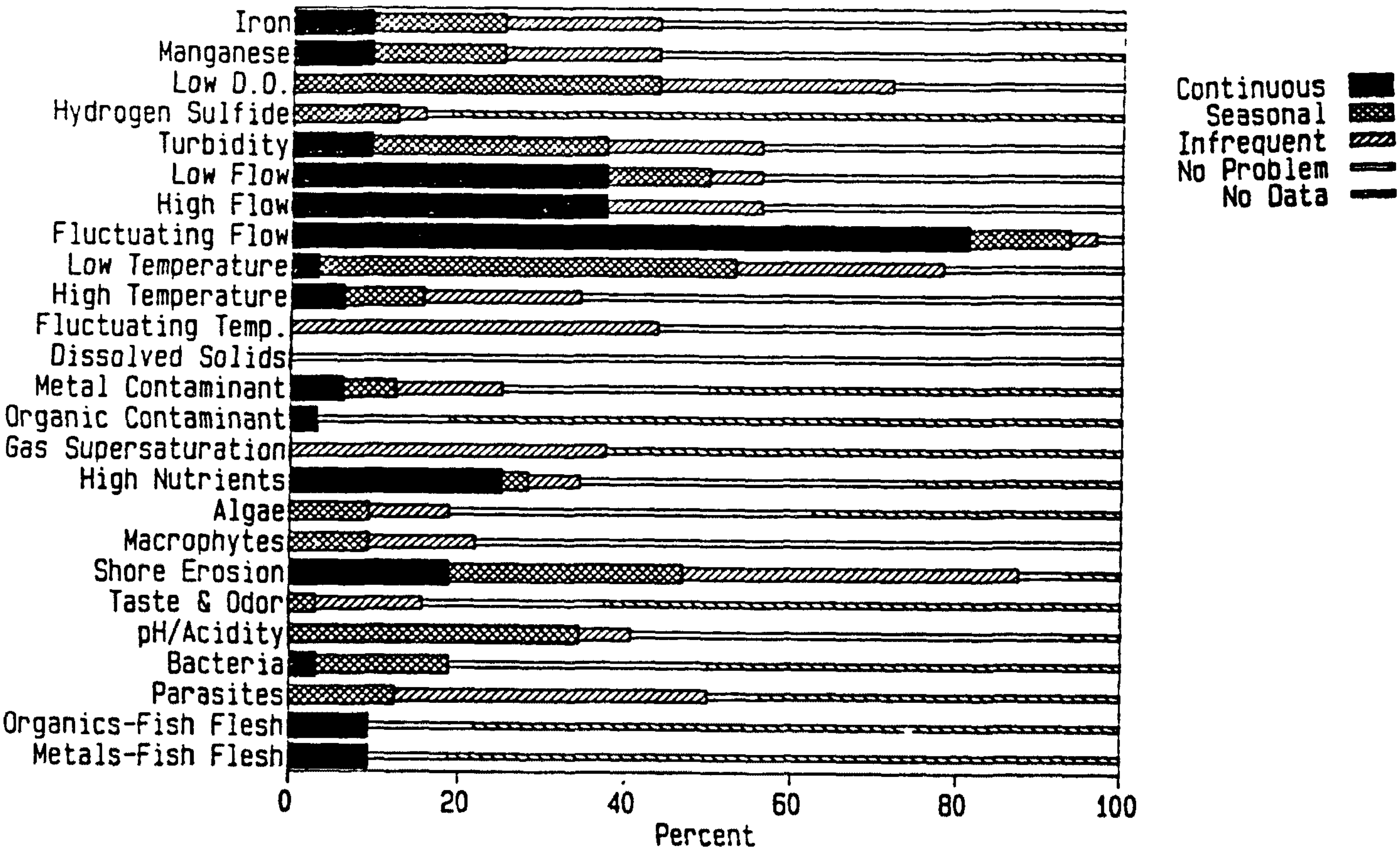




Figure 2. Rate of recurrence (upper graph) and user impact assessment for TVA reservoir pools for the indicated parameters.



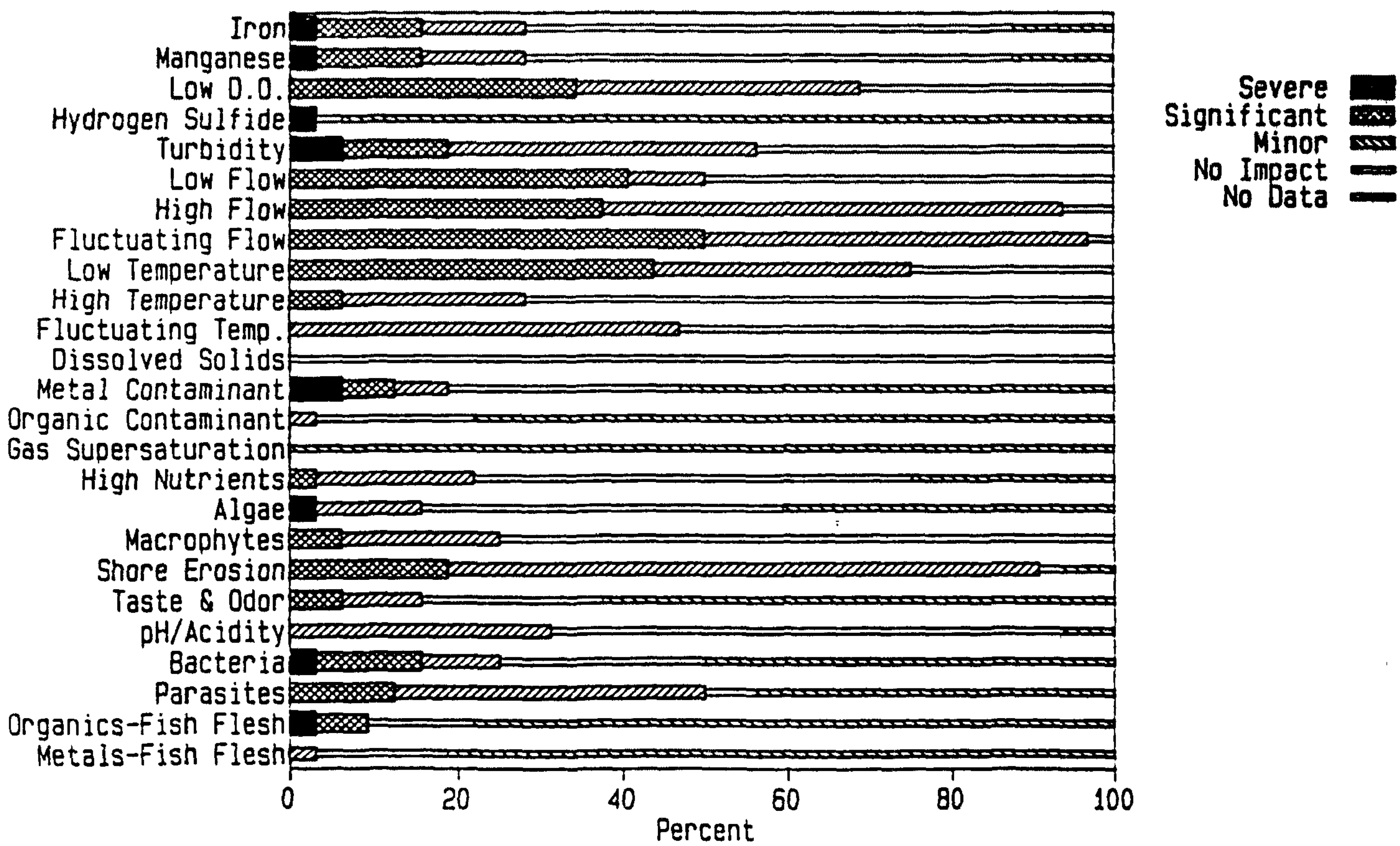




Figure 3. Rate of recurrence (upper graph) and user impact assessment for TVA reservoir tailwaters for the indicated parameters.

APPENDIX H
U.S. BUREAU OF RECLAMATION'S ASSESSMENT
SUPPLEMENT

EPA solicited comments from the States and Federal agencies for this report to Congress. Federal and non-Federal organizations with responsibility and activity involving impoundments were included. At the January 5, 1988, meeting the Tennessee Valley Authority (TVA), Bureau of Reclamation (USBR), and Corps of Engineers (COE) were invited to provide an agency assessment of water quality at their dams. Dams from these three agencies represent a wide range of geography, climate, and operational situations.

This chapter presents the results of these agency assessments. It utilizes an alternate approach to that used in the main body of this report. The three agencies felt there were important limitations in trying to perform a national overall assessment of the status of water quality at dams without detailed appreciation of regional effects. These limitations center on three main points:

1. **The basic assumptions of what constitutes a dam-related water quality problem are over-simplified.** The prime example of this is the assumption that thermal stratification in any reservoir with low level outlets automatically causes downstream problems of low dissolved oxygen, dissolved iron and managanese, and hydrogen sulfide. This is only the case where stratification lasts long enough to exhaust the supply of dissolved oxygen (DO) in the hypolimnion, and it is a function of the initial DO levels, the biochemical oxygen demand in the hypolimnion, and the hydrodynamics of flow through the bottom of the reservoir to the outlets. An examination of the USBR assessment presented below, for example, will show that problems of low DO, dissolved iron and manganese, and hydrogen sulfide are relatively rare at Bureau dams, although summer thermal stratification is nearly universal and low level outlets are not uncommon.

2. **The analytical tools used are too general and, in some cases, flawed.** The use of a Froude number calculated on the basis of a flow equal to the spillway capacity to estimate stratification potential is considered to have serious limitations. The Oak Ridge study cited in the evaluation of low DO levels in power dam releases is specific to the southeastern United States, and it is definitely not representative of USBR and COE power dams in the western arid region. An evaluation of downstream effects on the basis of a comparison of mean annual upstream and downstream data is not meaningful, in that it is not the annual average, but the seasonal variation that is important in an aquatic environmental parameter like flow or temperature. The r-enrichment analysis uses statistical models that have been shown to be too general for specific field situations.

3. **The data base (STORET) used in the analyses is not sufficiently comprehensive in its representation, has no control on the**

**quality or comparability of data on a case by case basis, and is arguably biased toward problem cases.**

Given these basic limitations, the agencies felt that conclusions reached on the basis of this overall evaluation are likely to be unreliable and unrepresentative.

As a result of these concerns, the three agencies were each asked to prepare a short assessment of the status of water quality at their dams. This gives an analysis of rather specific situations, with TVA dams located in a mature, well-developed and rather industrialized extended river basin; the COE dams are concentrated in the industrialized areas of the Southeast and the Ohio River Basin, coastal areas, the Pacific Northwest, and along main stem navigable rivers; and USBR dams are all in the western states.

In making their assessment, it was felt that a better approach to this subject is to, first of all, realize that dam-related water quality problems are much more site-specific than general. The case studies included in this report as Chapter IV make this point abundantly clear, while the agency assessments presented below further emphasize the variety of conditions.

The three agencies agreed that in this situation, the best way to assess the nature, extent, and severity of impact of dam-related water quality problems is to survey as many as possible of the existing impoundments and ask those directly responsible for their daily operation what the problems are and what impacts are being felt. They feel this subjective approach is more likely to yield an accurate assessment of actual conditions than is an indirect approach that relies on over-simplified assumptions, a "data-rich but information-poor"[1] data base, and the "illusion of technique"[2] of generalized models.

To this end, the three agencies adopted a questionnaire originally developed by Kennedy, Gunkel, and Gaugush of the U.S. Army Corps of Engineers Waterways Experiment Station (WES) at Vicksburg, Mississippi, as a uniform instrument for collecting dam-related water quality information on their respective projects. A copy of the questionnaire, with its instruction sheet, is attached at the end of this chapter (Attachment A).

Basically, the questionnaire presents field personnel with a comprehensive list of water quality attributes, and asks them to subjectively rate each attribute in the tributary, pool, and tailwater of

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[1] Ward, R.C., J.C. Loftis, and G.B. McBride. 1986. The "data-rich but information-poor" syndrome in water quality monitoring. **Environmental Management**, V.10, N.3, pp.292-297.

[2] Behnke, R.J. 1987. The illusion of technique and fisheries management. **Proceedings of the 22nd Annual Meeting of the Colorado-Wyoming Chapter of the American Fisheries Society**, March 11-12, 1987, Laramie, WY, pp.48-51.

each reservoir on the basis of the extent to which this attribute is a problem, the level of impact of the attribute on user benefits, and the reliability of the data upon which the rating is being made. A computer program, also developed at WES, compiles the data from the questionnaires into a SAS data file. Statistical analyses can then be performed on the various attributes and their ratings using the SAS software. In the short time allowed for this study, the three agencies limited their efforts to frequency analyses of each attribute's extent and impact in the pools and tailwaters of their reservoirs. Given more time, these analyses could be extended to reservoir tributaries and to the reported quality of available data. Finally, available quantitative data from agency files and STORET could also be added to the analyses, if there were a desire to go beyond an assessment of the situation to an investigation of parameter interrelationships.

The agencies feel the present limited analysis does, however, give an accurate picture of the known extent of given water quality conditions across a broad range of geography, climate, and project operating criteria, along with an assessment of the perceived impacts of these conditions on user benefits. All of this information is presented, not from the perspective of a simplified general overview of the way reservoirs should theoretically behave, but from the point of view of field personnel who are directly responsible for daily dam operations and the delivery of promised project benefits.

The remainder of this chapter contains the results of each agency's assessment of water quality related to its dams, beginning with the Bureau of Reclamation, and continuing through the Corps of Engineers and TVA. Each agency's section is organized as follows:

1. statement of policies and procedures followed by the agency in the development and management of water resources.

2. assessment of water quality with respect to the agency's dams.

3. recommendations for policies and practices for water quality aspects of dams and important related scientific and research needs.

## THE BUREAU OF RECLAMATION

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

Reclamation was formally begun 86 years ago with the passage of The Reclamation Act of 1902. In most areas of the 17 Western States, which constitute the area served by the Reclamation program, less than 20 inches of moisture falls each year. However, several important rivers, fed mainly by the melting snow packs in the mountains, flows through these States. A basic function of Reclamation is to harness these streams and to store their surplus waters in times of heavy runoff for later use when the natural flow is low.

Reclamation's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvment; flood control; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research in atmospheric water management and alternative energy sources, such as wind and solar power. Reclamation is also a primary source of research in design, construction, and development of materials used in water management structures. Reclamation programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

As of September 30, 1986, the Federal investment in completed Reclamation project facilities totaled $8.7 billion. This investment includes $1.7 billion in specific irrigation facilities, $1.7 billion in electric power facilities, $0.3 billion in municipal and industrial facilities, and $5.0 billion in multipurpose and other facilities. About 80 percent of this total investment is reimbursable to the Federal Treasury. Reclamation project facilities in operation during 1986 included: 355 storage reservoirs; 254 diversion dams; 15,804 miles of canals; 1,382 miles of pipelines; 276 miles of tunnels; 37,263 miles of laterals; 17,002 miles of project drains; 240 pumping plants; 50 hydroelectric powerplants; and 288 circuit miles of transmission lines. Nearly 10 million acres of Western farm land receive full or supplemental irrigation, over 20.5 million people receive municipal and industrial water, 53.2 million visitor days of recreation are recorded annually, and 13.8 million kilowatts of installed hydroelectric power capacity exists.

Completed water service facilities are transferred to local water user organizations for operation and maintenance as soon as the organizations become capable of assuming these functions. Reclamation operates and maintains hydroelectric powerplants and some water storage and supply works on multi-purpose projects. Of the 235 operating projects or units providing service in 1986, 172 were operated entirely by water user organizations, 39 were operated jointly by water user organizations and Reclamation, and 24 were operated entirely by Reclamation.

Unique Features of the Bureau of Reclamation

Among Federal programs, the Reclamation program is unique in several respects. First, it is regional in nature, it is limited by Reclamation Law to the 17 contiguous States lying wholly or partly west of the 100th meridian. Second, the Reclamation program has from the beginning, in contract to other Federal public works programs, been based on the principle of repayment by direct beneficiaries (water users, conservancy districts, power customers, etc.) As law and policy were revised and broadened over the years to accommodate multiple purpose projects, some program costs became nonreimbursable. The total amount repaid through fiscal year 1986 is over $2 billion, representing 23 percent of completed plant-in-service investment of $8.7 billion. Repayment of costs is greater in Reclamation than in any other Federal resource development program.

Another significant feature of the Reclamation program is the economic analysis that accompanies any proposed project. This evaluation consists of (1) plan formulations studies to determine optimum size and mix of features; (2) benefit-cost analysis aimed at the question of economic justification for the project; (3) cost allocation studies to assign costs to the various reimbursable and nonreimbursable functions; and (4) repayment analysis to determine if the project reimbursable costs can be repaid in accordance with requirements of law and policy.

## Reclamation's Salinity Control Program

A large body of law surrounds the Reclamation salinity control program and specific projects. The individual projects are subjected to congressional hearings, authorization and funding. In 1972, an amendment to the Federal Water Pollution Control Act, Public Law 92-500 (known commonly as the Clean Water Act) sets forth a public policy for restoration and maintenance of water quality standards, including benefical use designations and numeric salinity criteria. In June 1974, Congress enacted the Colorado River Basin Salinity Control Act, Public Law 93-320, which directed the Secretary of the Interior to proceed with a program to enhance and protect the quality of water available in the Colorado River for use in the United States and the Republic of Mexico. Reclamation is leading a strong and aggressive salinity control program launched by these acts of Congress.

The overall approach in meeting the salinity standards for the Colorado River is to prevent salt from entering and mixing with the river's flow. A number of agricultural, point, and diffuse sources of salinity have been identified in the Colorado River Basin. Reclamation's salinity control program will implement controls at those sites which contain salt sources that can be intercepted and prevented from entering the river at least cost.

The estimated salinity control program potential, through existing and planned Reclamation projects coordinated with State and other Federal agencies, has a projected total salt reduction in the Colorado River of 2.06 billion tons per year.

## The Changing Nature of the Reclamation Program

The shift in emphasis away from agriculture and toward municipal and industrial water, recreation, and fish and wildlife enhancement has been the trend for the past two decades. And as fewer large federally financed water projects are constructed, Reclamation is responding by developing alternative means of supplying water through improved system management, joint use of surface and ground-water supplies, and re-evaluating priority of use.

Management of water resources remains a critical necessity for the arid west. Reclamation is examing opportunities to increase water and power operating efficiencies and to identify opportunities for non-Federal partnerships for water resource development. The goals and the objectives of Reclamation are:

- Continue to provide the world's best engineering and construction expertise for water resource projects. Projects that are justified by local area need, support and funding.

- Improve efficiency by properly maintaining; upgrading and enhancing existing water and power resource facilities.

- Emphasize non-structural water efficiency and conservation alternatives.

- Maintain the technical water development capability to assist State, and local governments, as well as other non-Federal entities.

- Improve joint and multiple land and water resource use, including perfecting recharge and conjunctive use programs for ground water.

- Continue leadership in establishing effective and acceptable water quality programs and standards.

- Maintain the safety of the Nation's dams, reservoirs and waterways.

- Develop remedies for water-related hazardous waste problems.

## ASSESSMENT OF WATER QUALITY CONDITIONS IN BUREAU OF RECLAMATION RESERVOIRS AND TAILWATERS

Information on water quality conditions and user impacts for all Bureau of Reclamation (USBR) storage reservoirs and tailwaters was solicited by distributing a questionnaire (attachment A) developed at the Corps of Engineers Waterways Experiment Station (WES) to all six Bureau regional offices. All regions responded, and a total of 250 questionnaires were returned. The geographical distribution of this response by state is shown in figure 1. Since there are approximately 349 USBR storage reservoirs in eighteen western states (**USBR 1986**), this response represents nearly 72% of the total.

Information obtained on the frequency of occurrence of various water quality conditions in USBR reservoirs and their impact upon user benefits are summarized in figures 2 and 3, respectively. Tailwater conditions and their impacts are shown in figures 4 and 5, respectively.

What is most immediately apparent in these four figures is that in an average of 54% of the reservoir cases and 59% of the tailwater cases, there are no data upon which to make an evaluation of the conditions or their impact on user benefits. Further, if the assumption is made that the reason that no questionnaires were received on the other approximately 99 USBR reservoirs listed in the 1986 statistical compilation is that no data were available, then the total percentages of no data would rise to 68% for reservoirs and 71% for tailwaters.

Water quality data are usually only collected on a particular project when some problem is noted or suspected, or when some change in the structure or operation is contemplated. Consequently, the picture of water quality conditions in Bureau reservoirs and tailwaters given by the available information is probably somewhat skewed toward those situations where some problem is perceived or an impact is felt. The following assessment is, therefore, probably rather conservative.

Data sources for figures 6 through 9 are the same as figures 2 through 5, except that the percentages are based only on those cases for which data are available. The total number (N) of reservoirs or tailwaters with information on a particular condition is listed on the right side of each graph. These numbers range from 56 to 149, or from 16% to 43% of USBR storage reservoirs.

Figures 6 and 7 suggest that the main conditions affecting user benefits in Bureau reservoirs are drawdown, pool fluctuation, turbidity, sediment, and shore erosion. None of these are water quality conditions **per se**, but arise from the way water storage reservoirs are operated in an arid climate, where spring snowmelt or winter rains are the major source of runoff, and drawdown is continuous throughout the long dry season. Drawdown was rated as having a severe impact on user benefits in six USBR impooundments, and a significant impact in 33 others, out of a total sample of 107 reservoirs with information available. Thus, the cumulative percentage of reservoirs with data in which drawdown was rated as having at least a significant impact on user benefits is 36.4%. Corresponding cumulative percentages for the other four conditions are: pool fluctuation 35.3%, turbidity 13.2%, sediment 12.8%, and shore erosion 10.2%. The last condition, shore erosion, had no severe impact ratings out of a total of 108 impoundments rated.

The second most important set of reservoir water quality conditions affecting user benefits are related to eutrophication: algae, high nutrients, low dissolved oxygen, and taste and odor problems. Cumulative percentages of reservoirs with data where these conditions were rated as having at least significant impacts on user benefits were: algae 16.5%, high nutrients 15.2%, low dissolved oxygen 13.5%, and taste and odor problems 11.8%. There were no severe impact ratings for high nutrients or taste and odor problems, however.

Although iron is often present in Bureau reservoirs (figure 6), it was rated as having at least a significant impact on user benefits in only 4.4% of the rated reservoirs (figure 7). In fact, it should be noted that only drawdown and pool fluctuation were perceived as having really significant impacts on reservoir user benefits (figure 7).

Tailwater conditions and user impacts are depicted in figures 8 and 9, respectively. Here again, the major impact-producing conditions seem to cluster around the mode of operation of water supply reservoirs in an arid region: high flow, low flow, turbidity, and high temperature. Of these, high flow was rated as having significant user impacts in 21.1% of the tailwaters with data, but in no case was it rated as having a severe impact. The other three conditions were rated as having at least a significant impact in 13.2%, 11.6%, and 10.9% of the rated tailwaters, respectively. Taste and odor problems were rated as significant in 13.3% of the tailwaters with available data, but were not considered severe in any case.

## CONCLUSIONS

Three main conclusions may be drawn from this assessment of water quality in USBR reservoirs and tailwaters.

1. Data on water quality conditions and user impacts for about 30% of the Bureau's approximately 349 storage reservoirs are presented here. Since this group is somewhat biased toward projects where problems have been noted or suspected, the resulting assessment may be a bit pessimistic.

2. The main impact-producing conditions identified for Bureau reservoirs are drawdown and pool fluctuation, which are associated with a mode of operation that combines rapid spring filling of reservoirs with a steady withdrawal of water to satisfy irrigation, municipal, and industrial demands during the long dry season. These two conditions were rated as having at least significant impacts on user benefits in 36.4% and 35.3%, respectively, of the reservoirs with available data.

3. High flow was the main impact-producing condition noted in USBR tailwaters, probably reflecting the high spring inflows and spillway discharges of the mid-1980's. This condition was rated as having a significant impact on user benefits in 21.1% of the rated tailwaters, but in no case was the impact rated as severe. The next two impact-producing conditions cited were low flow and taste and odor problems, each with a cumulative rating of at least significant in about 13% of the tailwaters with available data. There were no severe ratings for tailrace taste and odor problems, however.

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U.S. Bureau of Reclamation. 1986. Statistical Compilation of Engineering Features on Bureau of Reclamation Projects. USBR, Denver, CO, 167 pp.

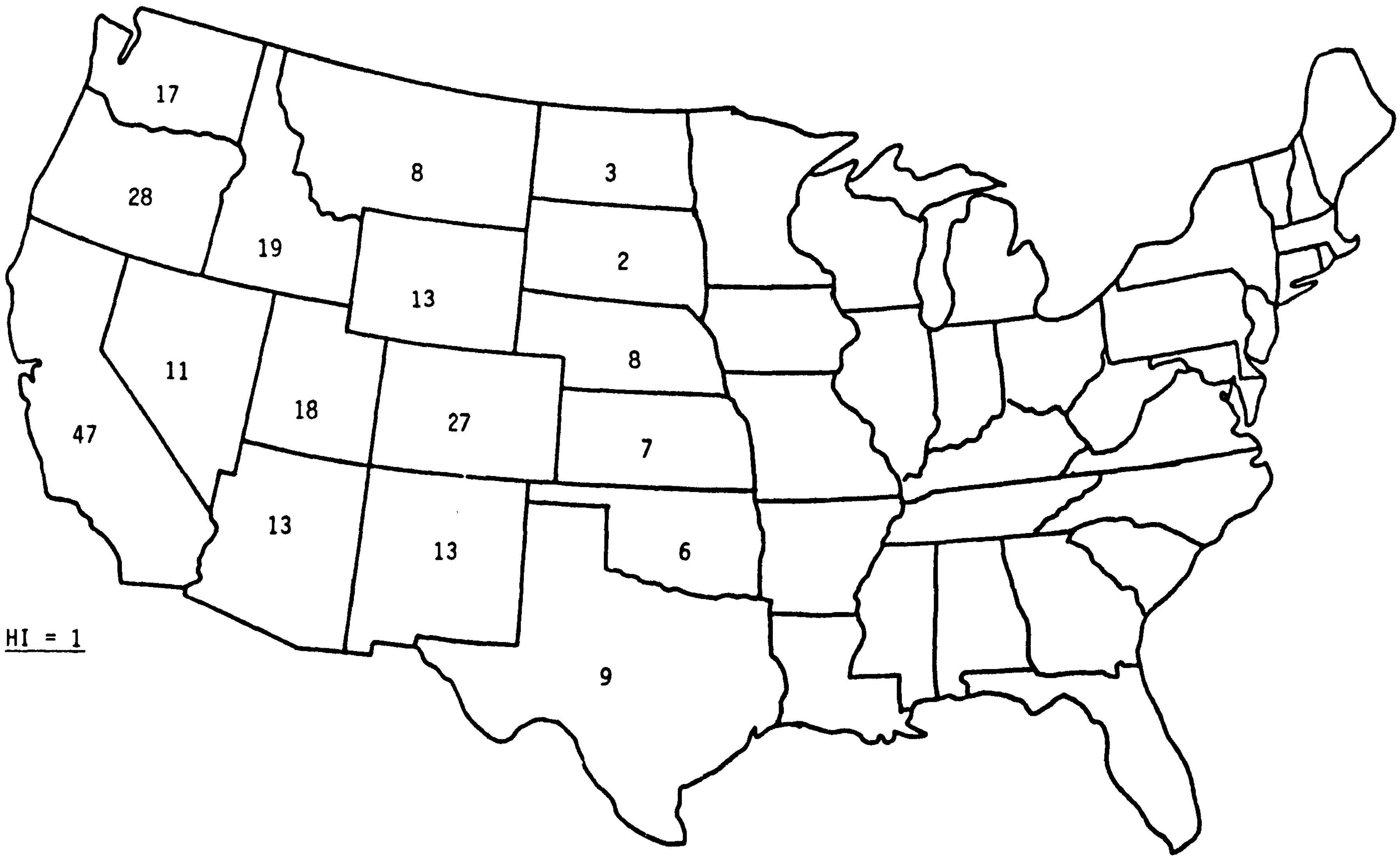



FIGURE 1. - Geographic Distribution of Responses to Water Quality Assessment of Bureau of Reclamation Reservoirs by State (Total = 250).

FIGURE 2. FREQUENCY OF OCCURRENCE OF WATER QUALITY CONDITIONS IN USBR RESERVOIRS(N=250)

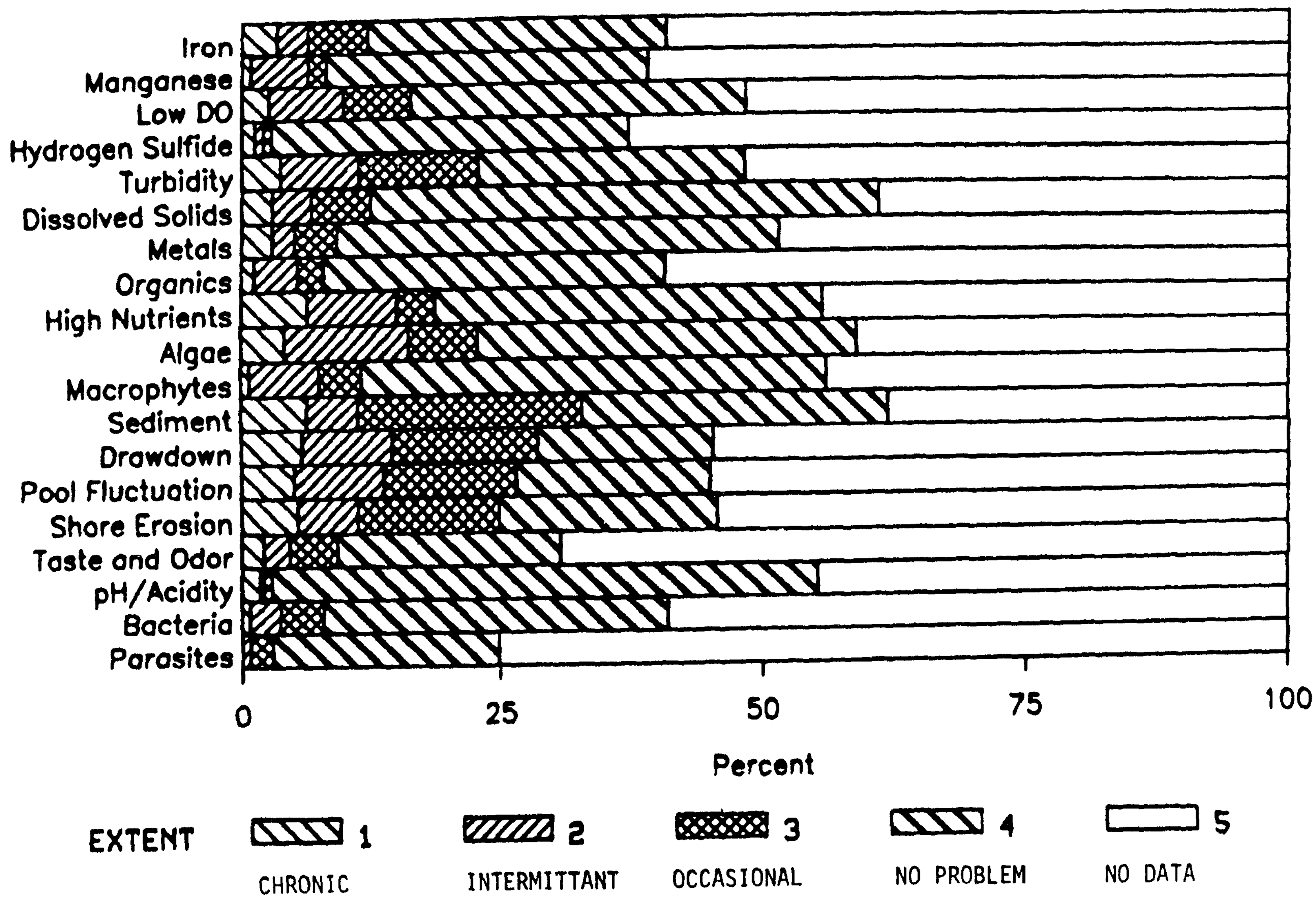


FIGURE 3. IMPACTS OF WATER QUALITY CONDITIONS ON USER BENEFITS AT USBR RESERVOIRS(N=250)

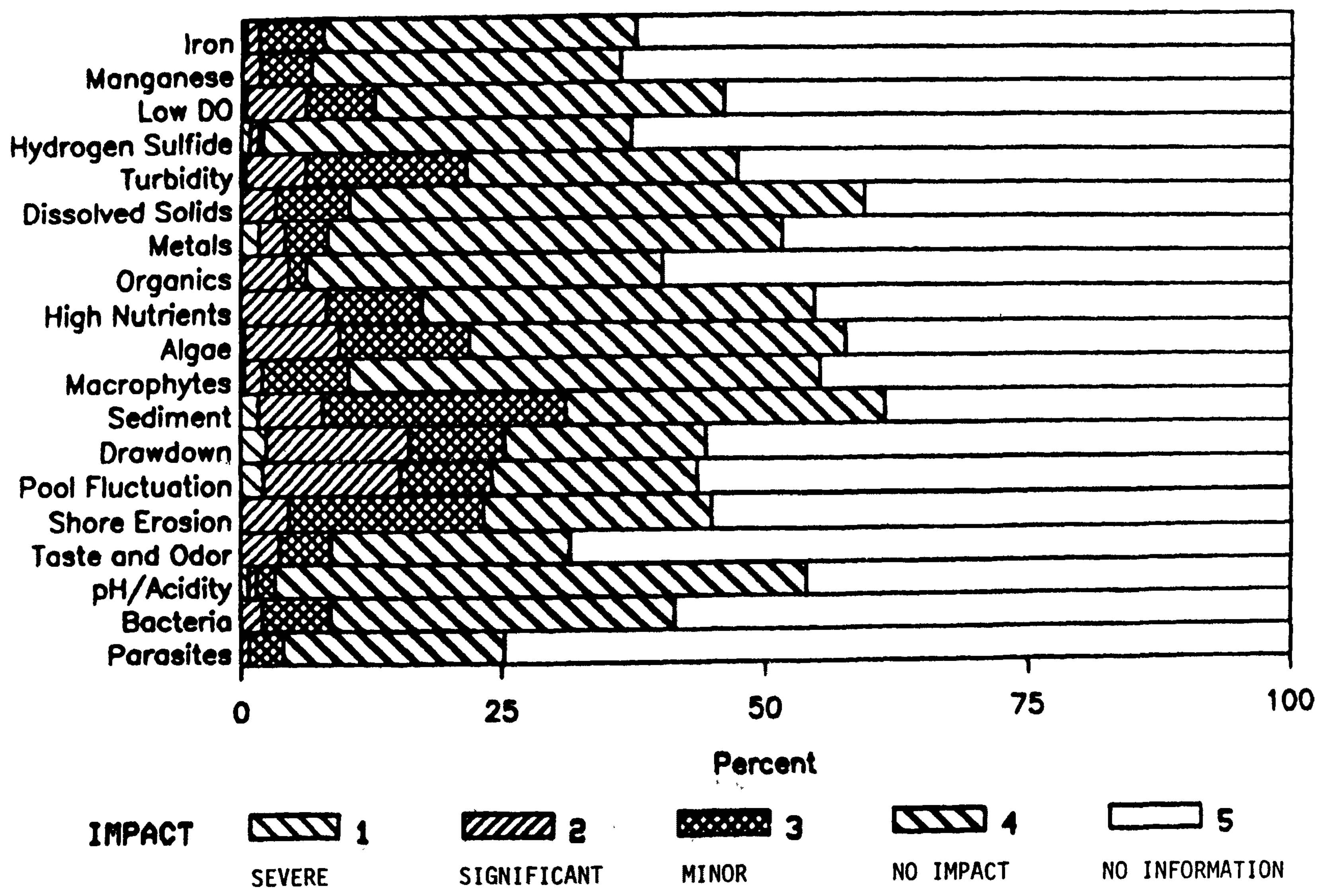


FIGURE 4. WATER QUALITY CONDITIONS IN TAILWATERS OF USBR RESERVOIRS(N=250)

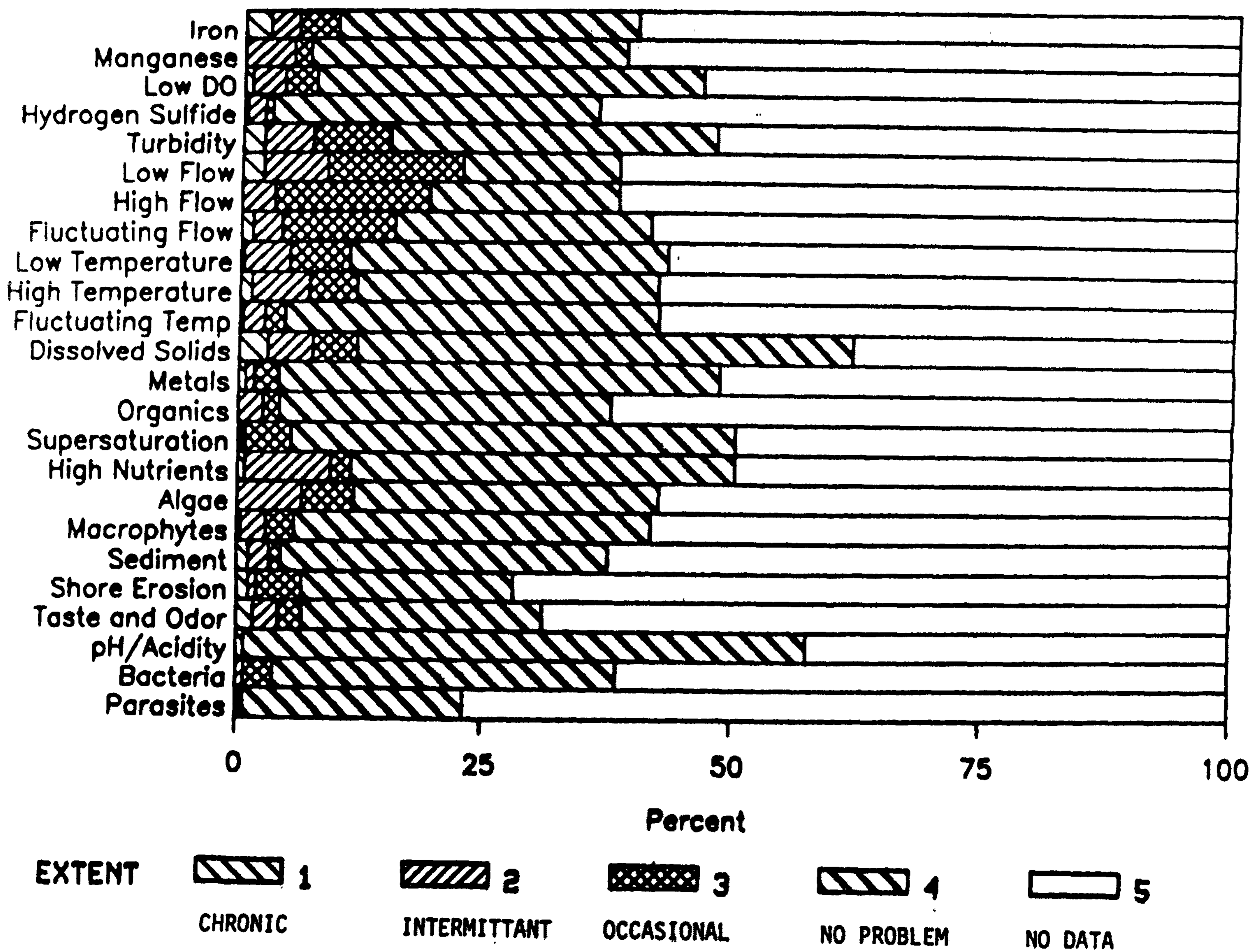


FIGURE 5. IMPACTS OF WATER QUALITY ON USER BENEFITS – TAILWATERS(N=250)

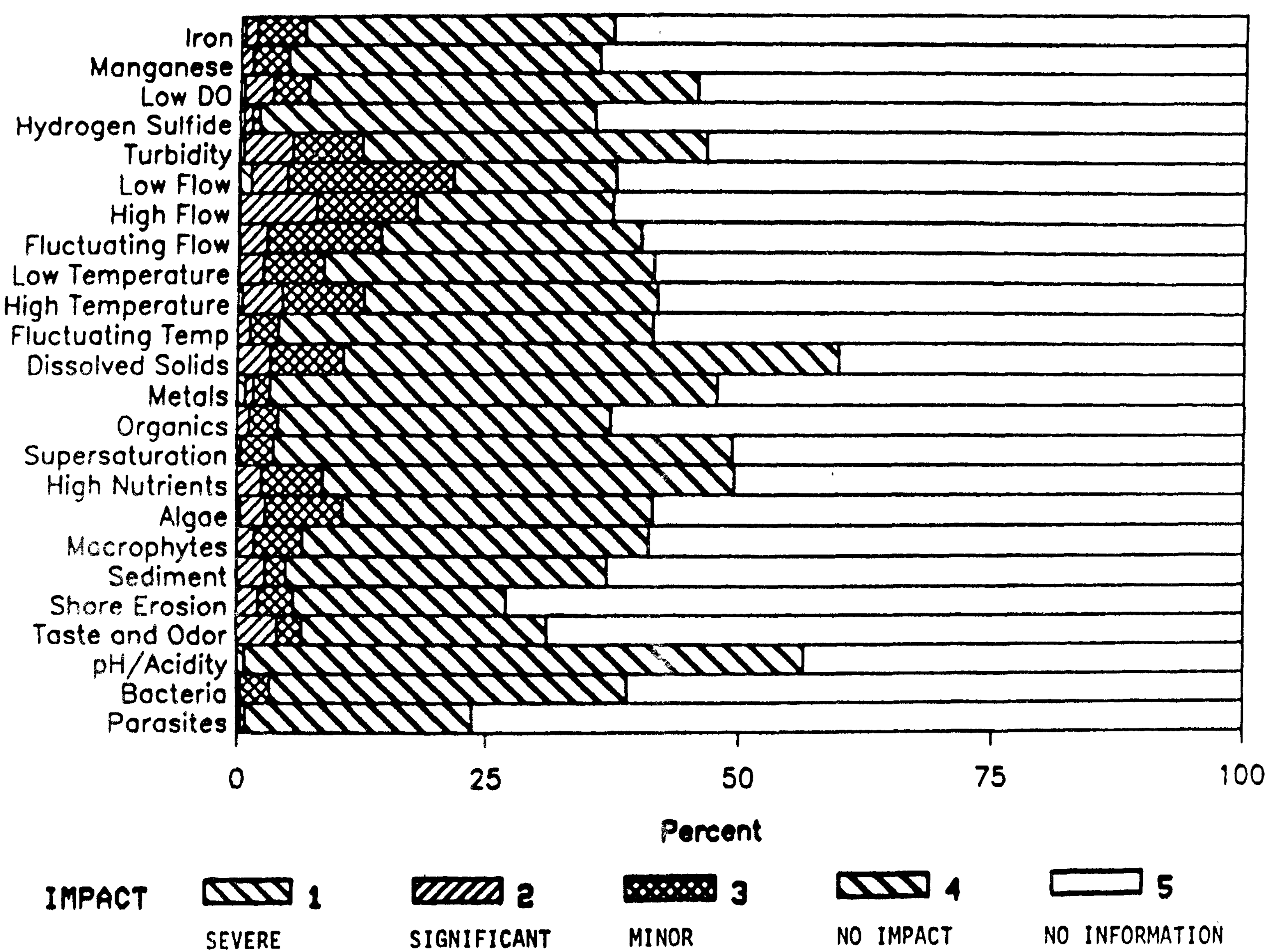


FIGURE 6. FREQUENCY OF OCCURRENCE OF WATER QUALITY CONDITIONS IN USBR RESERVOIRS(N VARIES)

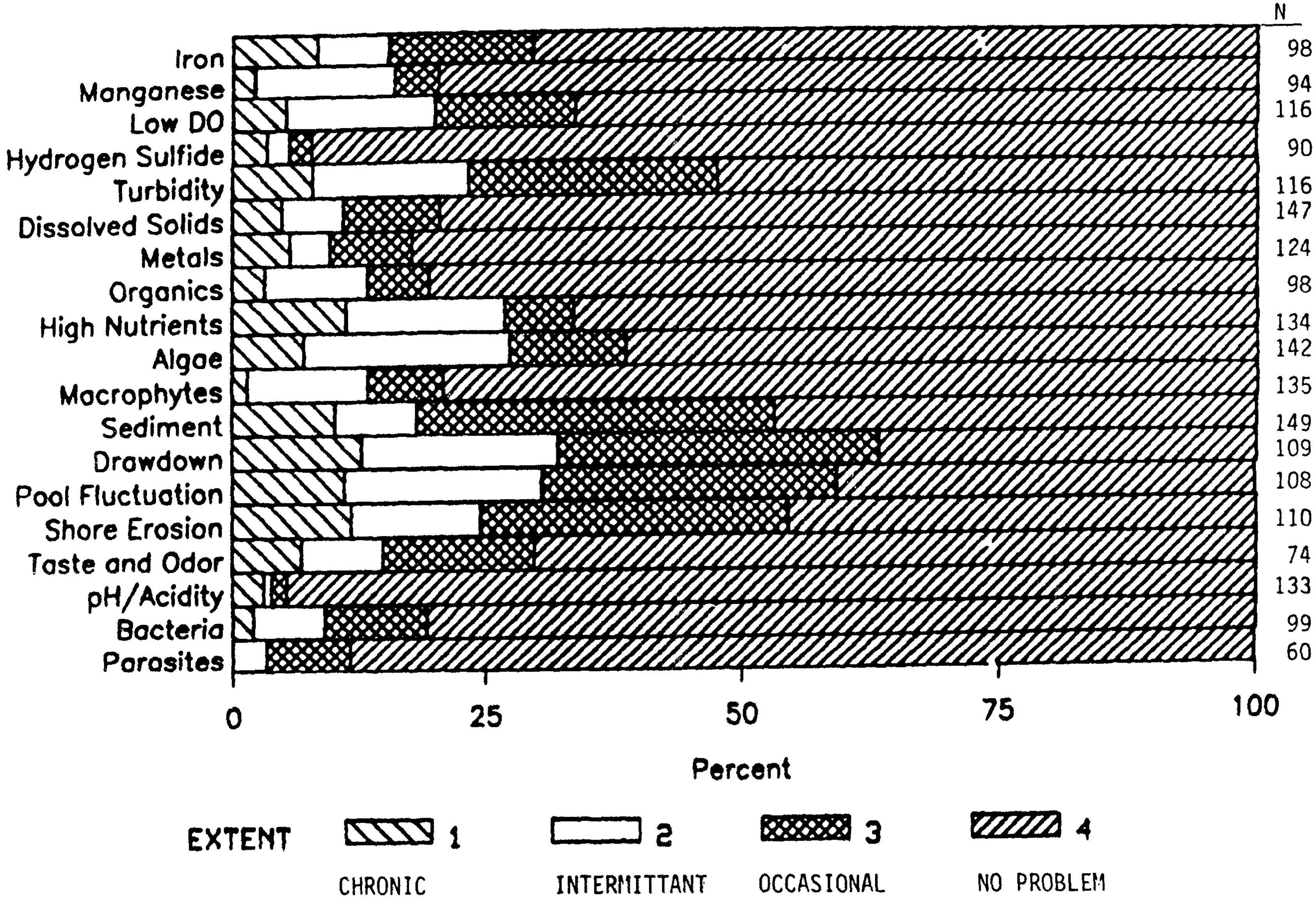


FIGURE 7. IMPACTS OF WATER QUALITY CONDITIONS ON USER BENEFITS AT USBR RESERVOIRS(N VARIES)

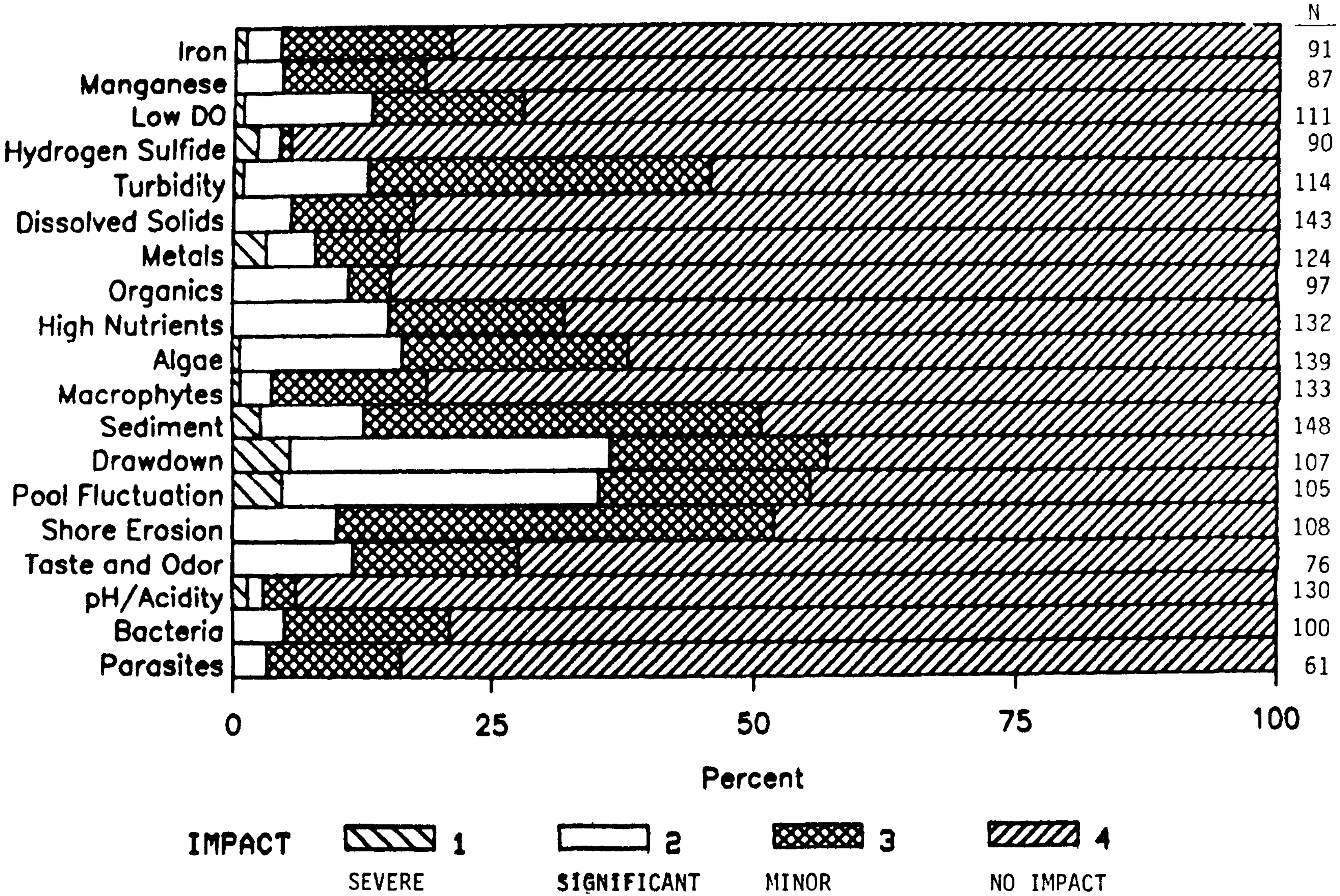


FIGURE 8. WATER QUALITY CONDITIONS IN TAILWATERS OF USBR RESERVOIRS(N VARIES)

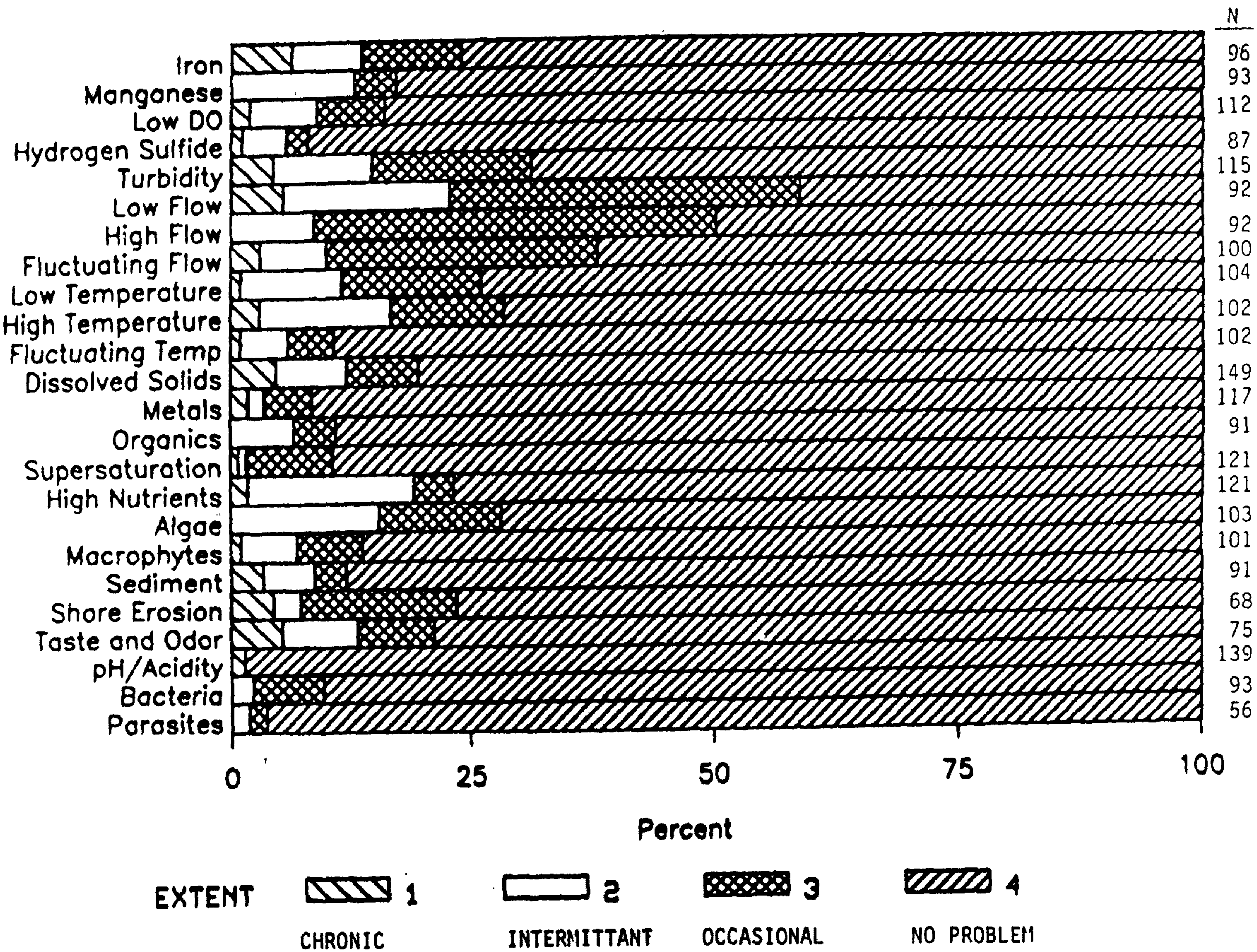
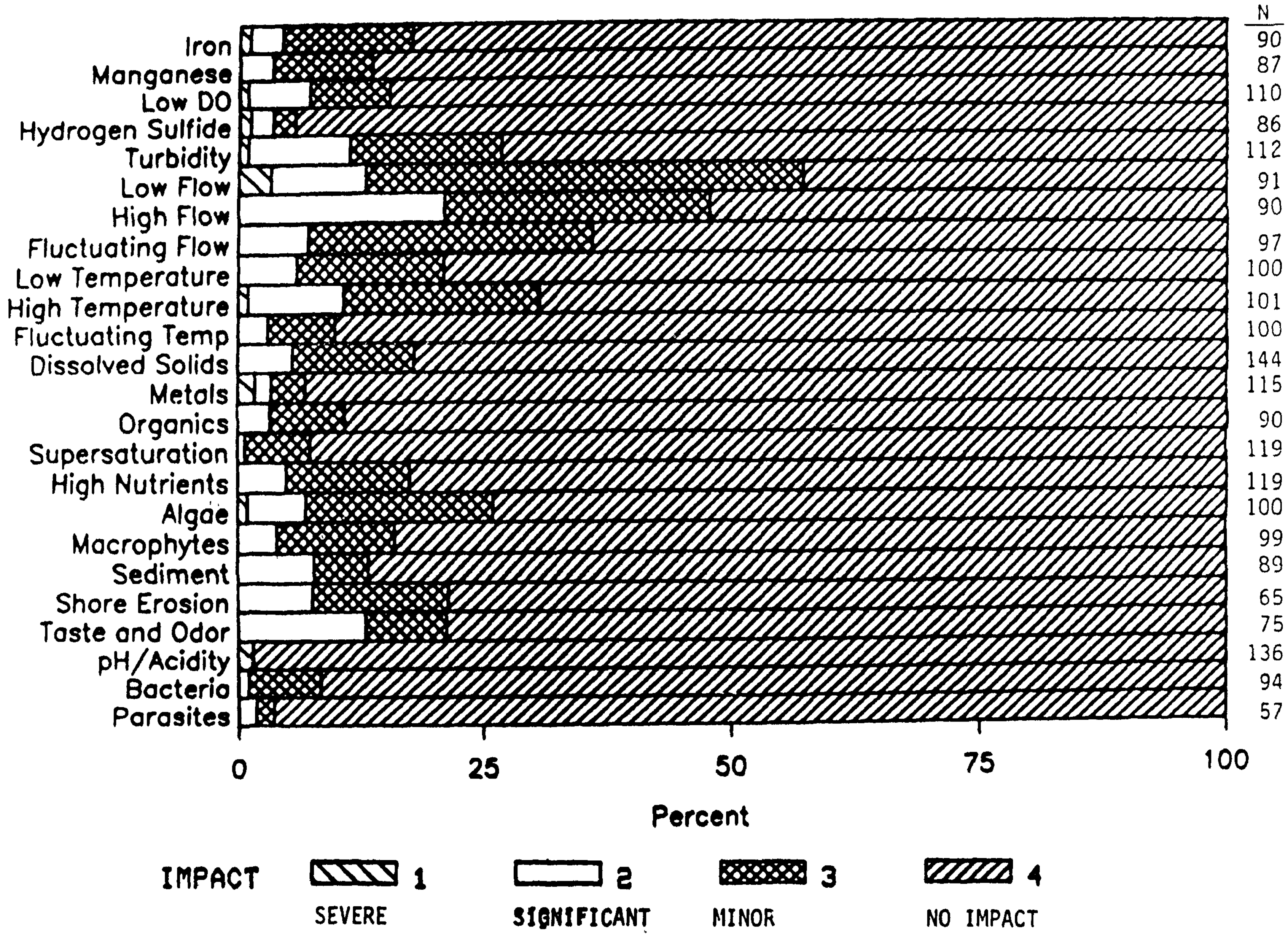


FIGURE 9. IMPACTS OF WATER QUALITY ON USER BENEFITS — TAILWATERS(N VARIES)



## RECOMMENDATIONS

The following recommendations represent ideas that should help Congress better evaluate water quality (WQ) issues relating to dams and impoundments. All of the ideas are more or less related and will have direct implications for all of the water resource management agencies (USBR, COE, TVA, referred to as the Agencies). The principal policy implications of these recommendations are that the Agencies will need to shift more priority towards WQ issues and cooperate to accomplish technical goals. Thus coordination between the Agencies will be a primary requirement of these initiatives. The section following the recommendations provides a suggested organizational structure for these activities.

**1. Avoid establishing uniform standards for WQ of impoundments and dam discharges that ignore regional differences between reservoirs and the often conflicting demands of water users.**

A cursory examination of the WQ summaries seen in Figures 2 through 9 reveals that the problems identified for reservoirs in the arid West are very different from those in the East. Nutrient loading and eutrophication are the principal concern for TVA reservoirs that are located in a much more industrialized and densely populated area. In the West, pool fluctuations and flow are the major concern for USBR reservoirs.

Most projects must plan the O&M of their reservoirs to balance the WQ (or water supply) demands of many user groups, each with often contradictory requirements. Each reservoir has a unique set of water uses and range of WQ conditions, and compromises are often necessary since WQ cannot always be maximized for every user. Rigid WQ standards would ignore the complexity of reservoir O&M vs. user WQ demands, and remove the flexibility necessary to prioritize water uses.

For example, selective withdrawal to maximize downstream WQ for fisheries may conflict with protection of WQ in the reservoir. Reservoir fisheries and recreation may suffer to benefit downstream fisheries or vice versa. Resolving such issues is difficult and requires that the Agencies maintain management flexibility to prioritize water uses. While uniform WQ standards do represent a simple and expedient approach, they would prevent the Agencies from considering the complex mix of user demands necessary to properly manage reservoirs.

**2. Establish a common geographic information system/data base (GIS/DB) for all national water resource agency impoundments.**

One of the major difficulties in studying this subject on a national scale is the lack of a unified data set with comprehensive and unbiased information. Given the current situation where each agency has incomplete and unvalidated data sets stored in incompatible computer formats (or in printed summaries), it is difficult to make an accurate or reasonably precise evaluation of dam water quality problems at the national level.

Water quality problems do not occur regularly in impoundments or in downstream releases. However, in certain situations, depending upon many factors discussed in this report, water quality problems can and do occur. Preventative measures must then be instituted in new projects or corrective actions taken at existing facilities. In order to identify the locations, causes, and nature of water quality problems, an inventory of water quality at major Federal impoundments is needed. Such a data base would be a valuable resource for improved management of national water resources. Inventories by Reclamation, COE, and TVA, prepared on a compatible basis, would contain information typical of most situations in the U.S. With proper coordination with non-Federal dam owners, the usefulness and scope of these three data bases could be further expanded.

The Agencies should establish a common, validated GIS/DB that would contain layers of data currently available from other sources (USGS, EPA, etc,) along with data specifically related to water projects.

A common format, distributed GIS would allow the retrieval of other agency data when needed and would provide Congress, and State and Federal environmental enforcement agencies rapid access to both quantitative data and subjective evaluations for water quality in reservoirs. This would facilitate improved decision processes for identifying water quality problems and provide a means for researchers, planners, and policy makers to evaluate the relationships between water quality and other variables such as land use, population, reservoir morphology, pollution sources, and O&M strategies.

Technical Aspects

Examples of currently available digital data sets that could be of use in evaluating the water quality problems of impoundments include:

- ** USGS digital elevation data
- ** USGS streamflow and Benchmark Sample WQ data
- ** USGS bedrock geology maps
- ** SCS soil classification (mineralogy) maps
- ** USDA crop cover maps
- ** USFS timber cover maps
- ** Specific land classification and vegetative cover studies based on digital analysis of remote sensing data and satellite images
- ** EPA STORET water quality data
- ** EPA National Surface Water Survey alkalinity

maps

** Subjective evaluations of WQ problems, severity, and frequency from COE data set
** USBR acid precipitation sensitivity data
** Engineering blueprints for TVA, COE, USBR dams
** Population and economic data
** NOAA meteorological data
** Historical O&M records
** Hydrology data for specific projects
** Dam safety data for specific projects

The Agencies should agree to adopt hardware, software, and data format protocols currently being used and developed by the USGS in order to take advantage of available digital data sets and to ensure data compatability. ARC/INFO is a GIS/DB that is widely used and is available on VAX minicomputers. USGS is also developing microcomputer-based GIS systems that rely on compact disk technology to store large data sets.

By adopting standard configurations, a lower-cost, distributed approach to the GIS/DB can be used that eliminates the need for expensive mainframe computers and management of a centralized "super" data system. Each individual Agency would be responsible only for data directly related to their projects, and would import other data sets for specific data evaluation tasks. In a similar manner, national evaluations could be performed by temporarily combining the Agency records for the most recent information.

The final, and possibly most important aspect of this effort involves implementation of a thorough quality assurance/quality control (QA/QC) program for data entered into the GIS/DB. This would address the issues of reliability of existing data, establishment of appropriate techniques for WQ sampling and chemical analyses, and procedures for documentation, error detection and correction. The major portion of these protocols have already been established by EPA and USGS, so minimal development time will be required.

Policy Implications

The most significant policy implications of the GIS/DB will be the necessity of securing development and long-term maintenence funding from Congress, and adjusting Agency priorities to reflect a stronger and more consistent committment to water quality issues. To this end it is recommended that Congress be provided with information that would encourage the development of this GIS/DB. Also, the ongoing USGS GIS activities should be encouraged and promoted by the water resources agencies.

The development of a GIS/DB represents a complex task that will require careful planning and coordination between the water resource agencies, EPA, USGS and several other Federal and State agencies. While organizational structures are in place for coordination between the water resource agencies, development of a GIS/DB will require a wider and more comprehensive coordination effort.

We would recommend that an Interagency Management Oversight Group be formed to guide the development of the GIS/DB (and other WQ-related initiatives). A permanent GIS/DB Working Task Group, comprised of technical personnel who would be responsible for implementing and maintaining the system, and providing the inter-agency peer-communication necessary to maximize available resources and prevent costly duplication of effort, should be appointed.

Members of the Management Oversight Group would provide policy review, help to champion the GIS/DB concept inside their respective agencies, and encourage the proper funding priority to ensure a successful effort.

**3. Pursue Congressional appropriations to adequately fund reservoir monitoring programs.**

One of the major problems with the STORET WQ data used in the contractor report is that the available reservoir data is usually collected during problem episodes, thus introducing significant bias in the data. Also, WQ monitoring programs are inconsistently funded, often resulting in non-representative data sets, poor planning, lack of sampling design or quality assurance. In order to address these problems, the following is recommended:

> ** Establish a standard funding period for post-impoundment and post-mitigation action monitoring.
>
> ** Develop a stratified, randomized monitoring program, much like the EPA Surface Water Survey, that would provide an unbiased background data set to use for national WQ evaluations in reservoirs.
>
> ** Develop Congressional committment to WQ by encouraging a consistent, long-term approach to funding of reservoir WQ monitoring.
>
> ** Ensure that monitoring is performed in accordance with accepted QA/QC protocols to guarantee quality of data.
>
> ** Include validated data in the reservoir GIS.

Technical Aspects

Monitoring should be performed with an adequate QA/QC program in place, and resulting data should be included in the GIS/DB. Development of a statistically randomized "background" sampling program will be based on currently accepted methods for water quality sample network design.

Policy Implications

This recommendation is closely related to the GIS/DB initiative and shares many of the policy issues identified above. While Congress would have to appropriate funding for monitoring activities, it is also important to remember that the Agencies must also develop an internal committment to water quality and monitoring that will ensure consistent long-term priority.

Establishment of a common QA/QC program for reservoir monitoring, a task that will also be important to the GIS/DB, will require coordination between the Agencies. It is recommended that the QA/QC and the water quality monitoring network design for the randomized program be developed by an interagency technical group with review by EPA and statisticians familiar with sampling design.

**4. Develop better methods for measuring the relationship between WQ problems and effects on user benefits.**

A discussion of water quality problems implies an adverse effect on some recognized use of the water; e.g., drinking water, body contact recreation, fish production, or agriculture. In recent years, the economic impacts of salinity have been measured and are currently used to select cost-effective alternatives for meeting treaty WQ obligations for the Colorado River. Unfortunately, there is no such standardized approach or methodology available to quantify relationships between concentrations of WQ constituents and the effects on user benefits or costs. Thus, it is difficult to assign costs to WQ problems or the mitigation strategies chosen for a given problem.

By developing these relationships, agencies could prioritize corrective action plans based on the severity of impacts to economic benefits, recreational use, or intangibles such as aesthetic quality. This prioritization would also assist in the planning and design of cost-effective mitigation measures.

Technical Aspects

This process would involve applied research to develop and/or evaluate existing methods for quantifying the costs (or loss of benefits) associated with specific WQ constituents. Such an effort would require expertise in risk assessment and related statistical specialties.

Policy Implications

Investigation and implementation of this idea will once again require coordination between the Agencies, and an appropriate technical task group should be formed that will report to the

Interagency Management Oversight Group. Policy guidance will also be needed to establish appropriate risk factors inherent for different WQ constituents and intended reservoir use.

**5. Encourage public involvement in reservoir WQ issues by establishing Citizen Advisory Boards or Councils.**

Citizens' Advisory Councils would help the Agencies identify priority WQ issues in reservoirs and provide an organized mechanism for public input or advise. Such Councils or Boards would also help Agencies in several other important ways:

** Advisory Council(s) would foster a more cooperative relationship between agencies, environmental groups, user interest groups, and the general public. The net result would be a more positive public image for the agencies and a more obvious committment to water quality issues.

** Good communication regarding WQ problems from the public would prevent embarrassing public relations problems due to lack of responsiveness through the usual bureaucratic channels.

** The Advisory Council(s) would help provide lobbying influence for funding of research and monitoring of WQ problems in reservoirs.

Technical Aspects

None, although informed technical personnel should be involved in Advisory Council activities.

Policy Implications

Once again, coordination between agencies should be important. Advisory Councils may be nationally-oriented, however, it is more likely that they will be of local interest. One agency's experience with a particular problem could be very valuable in helping another deal with the public on sensitive environmental issues. An interagency task group that meets occasionally should provide the means for effectively sharing such experiences.

****************************

**The recommendations detailed above should be coordinated according to the organizational chart detailed on the following page.**

Organizational Structure for implementation of WQ recommendations

******************************************
* INTERAGENCY MANAGEMENT OVERSIGHT GROUP *
******************************************

Personnel: Agency administrators with WQ experience

Function: Policy oversight, program funding and
advocacy, Congressional liason

*
*
*
*
*

**************************
* GIS/DB Technical Group *
**************************

Personnel: Technical with GIS and computer experience

Function: Develop and coordinate approach, procurement and IAGs,
and actual implementation of system

*
*
*
*
*

******************************
* Risk/Cost Assessment Group *
******************************

Personnel: Technical with EIS, risk analysis and statistics
experience.

Function: Develop and implement assessment methodology

*
*
*
*
*

***************************************
* Advisory Council Coordination Group *
***************************************

Personnel: Administrative with WQ and public relations experience

Function: Communication between Agencies on WQ Issues

APPENDIX I
AGENCY QUESTIONNAIRE USED IN
DEVELOPING ASSESSMENTS
SUPPLEMENT

Information is needed to prepare a summary statement on the present status of water quality at Bureau dams. This will be used in a section prepared by the Bureau for a report by EPA to be submitted to Congress on water quality and dams.

INSTRUCTIONS

For each dam, complete the questionnaire using available information and knowledge based upon day-to-day familiarity with the project.

Water Quality Evaluation

For dams or items for which information is not available, enter: NIA.

Provide the name of the dam, project, and category using the following:

Category

A. Constructed and operated by Bureau of Reclamation

B. Rehabilitated and operated by Bureau of Reclamation

C. Constructed by others, operated by Bureau of Reclamation

D. Under construction by Bureau of Reclamation

E. Constructed by Bureau of Reclamation, operated by others

F. Rehabilitated by Bureau of Reclamation, operated by others

G. Constructed and operated by others

H. Constructed under loan program

The evaluation table lists several commonly cited water quality considerations for reservoir projects. For each water quality consideration and each project location type (i.e., tributary, pool, and tailwater), evaluate the extent of the problem (Column a), the relative impact on user benefits (Column b), and the reliability of data upon which the evaluation is based (Column c). Brief remarks which would aid in the interpretation of this information may be entered where indicated.

Problem Evaluation (Column a)

Code
- 0 :No problem evaluation has been made.
- 1 :Chronic or continuous problem.
- 2 :Intermittent problem occurring on a seasonal or event basis.
- 3 :Occasional problem occurring infrequently on an annual basis.
- 4 :No problem.

User Impact (Column b)

Code
- 0 :Information concerning user impacts is not available.
- 1 :Severe impact resulting in the longterm loss of one or more user benefits.
- 2 :Significant impact which restricts but does not eliminate user benefits.
- 3 :Minor impact which does not restrict user benefits.
- 4 :No impact on user benefits.

Data Reliability (Column c)

Code
- 0 :Data or information are not available.
- 1 :Based on reliable data covering appropriate time frame.
- 2 :Based on scattered or incomplete data.
- 3 :Based on informal information.

Water quality considerations for which evaluations are requested are briefly described below.

Iron - Elevated concentrations of dissolved or particulate iron.
Manganese - Elevated concentrations of dissolved or particulate manganese.
3. Low Dissolved Oxygen - Concentrations below saturation.
4. Hydrogen sulfide - Elevated concentrations or obvious odors.
5. Turbidity - Reduced water clarity due to suspended inorganic solids.
6. Low Flow - Insufficient flow in the tailwater.
7. High Flow - Excessive discharge flows in the tailwater.
8. Fluctuating Flow - Excessive or unnatural changes in flow.
9. Low Temperature - Temperature below expected or desirable level.
10. High Temperature - Temperature above expected or desirable level.
11. Fluctuating Temperature - Undesirable changes in temperature.
12. Dissolved Solids - Elevated concentrations of total dissolved solids.
13. Metal Contaminants - Elevated concentrations of metals other than iron and manganese.
14. Organic Contaminants - Presence of man-made organic compounds.
15. Gas Supersaturation - Dissolved nitrogen gas concentration above saturation.
16. High Nutrients - Excessive nitrogen and phosphorus concentrations.
17. Algae - Excessive algal biomass or chlorophyll concentration.

18. Macrophytes - Excessive or undesirable growths of rooted or floating aquatic plants.
19. Sediment Accumulation - Excessive or undesirable sediment accumulation.
20. Drawdown - Prolonged periods of low pool elevation with undesirable impacts.
21. Pool Elevation Fluctuation - Undesirable impacts due changing pool.
22. Shoreline Erosion - Loss of banks or shoreline due to erosion.
23. Taste and Odor - Taste or odor in raw and/or finished potable water.
24. pH or Acidity - pH significantly below neutrality or high level of acidity.
25. Bacteria - Excessive levels of any microbe.
26. Parasites - Presence of any animal or human parasite.
27. Other - Specify other water quality considerations as needed.
28. Other - Specify other water quality considerations as needed.
29. Other - Specify other water quality considerations as needed.
30. Other - Specify other water quality considerations as needed.

1. Dam: ______________________ 2. Project: ______________________

3. Category: ______________________

| Water Quality Consideration | Tributary | | | Pool | | | Tailwater | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | a | b | c | a | b | c | a | b | c | |
| 1. Iron | | | | | | | | | | |
| 2. Manganese | | | | | | | | | | |
| 3. Low D.O. | | | | | | | | | | |
| 4. Hydrogen Sulfide | | | | | | | | | | |
| 5. Turbidity | | | | | | | | | | |
| 6. Low Flow | | | | | | | | | | |
| 7. High Flow | | | | | | | | | | |
| 8. Fluctuating Flow | | | | | | | | | | |
| 9. Low Temperature | | | | | | | | | | |
| 10. High Temperature | | | | | | | | | | |
| 11. Fluctuating Temp. | | | | | | | | | | |
| 12. Dissolved Solids | | | | | | | | | | |
| 13. Metal Contaminant | | | | | | | | | | |
| 14. Organic Contamin. | | | | | | | | | | |
| 15. Gas Supersaturat. | | | | | | | | | | |
| 16. High Nutrients | | | | | | | | | | |
| 17. Algae | | | | | | | | | | |
| 18. Macrophytes | | | | | | | | | | |
| 19. Sediment Accum. | | | | | | | | | | |
| 20. Drawdown | | | | | | | | | | |
| 21. Pool Elev Fluct. | | | | | | | | | | |
| 22. Shore Eros. | | | | | | | | | | |

Water Quality Description (Continued):

| Water Quality Consideration | Tributary | | | Pool | | | Tailwater | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | a | b | c | a | b | c | a | b | c | |
| 23. Taste and Odor | | | | | | | | | | |
| 24. pH/Acidity | | | | | | | | | | |
| 25. Bacteria | | | | | | | | | | |
| 26. Parasites | | | | | | | | | | |
| 27. Other (________) | | | | | | | | | | |
| 28. Other (________) | | | | | | | | | | |
| 29. Other (________) | | | | | | | | | | |
| 30. Other (________) | | | | | | | | | | |

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