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	Engineering and Design RESERVOIR WATER QUALITY ANALYSIS	
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DEPARTMENT OF THE ARMY
U. S. Army Corps of Engineers
Washington, DC 20314-1000

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30 June 1987

Engineer Manual
No. 1110-2-1201

Engineering and Design
RESERVOIR WATER QUALITY ANALYSIS

1. *Purpose*. This manual provides guidance for the assessment of reservoir water quality conditions, including reservoir pool, releases and tailwaters.

2. *Applicability*. This manual applies to all HQUSACE/OCE elements and field operating activities (FOA) having responsibility for water quality/quantity control. It provides a framework to guide Corps of Engineers scientists and engineers in assessing water quality conditions associated with reservoirs.

3. *Discussion*. Early reservoir water quality assessment activities were based on techniques and processes commonly accepted in standard limnology and sanitary engineering. However, approaches to assessing and solving reservoir water quality problems were often found to be insufficient due to processes and water control operations inherent to reservoirs. Some of these problems interfere with project purposes and/or result directly from water control (reservoir regulation) practices. Many of these problems were addressed by the Environmental and Water Quality Operational Studies (EWQOS) research program, and new technologies pertinent to reservoir water quality have been developed. Much of the material in this manual is a product of this program and of field experience from Corps district and division offices.

FOR THE COMMANDER:

RC Lee

Robert C. Lee
Colonel, Corps of Engineers
Chief of Staff

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CHAPTER 1

INTRODUCTION

Section I. General

1-1. Purpose. This manual provides guidance for the assessment of reservoir water quality conditions, including reservoir releases and tailwaters. Procedures are generally presented without theoretical discussion, since these details can be found in referenced sources.

1-2. Applicability. This manual applies to all field operating activities having responsibilities for reservoir water quality/ quantity control. It provides a framework to guide Corps of Engineers scientists and engineers in assessing water quality conditions associated with reservoirs. Emphasis is placed on procedures to define program and/or study objectives and to select appropriate techniques for assessing water quality conditions in the planning, design, and water control management of reservoirs.

1-3. Reference. The references are indicated throughout the manual by numbers that correspond to similarly numbered items in Appendix A.

1-4. Background.

a. Environmental concern expressed by the public through the Congress has resulted in the passage of Federal legislation and the issuance of Executive Orders directing increased efforts by Federal agencies in water quality management. Initial legislation on water quality management was directed toward public health and water supply. Subsequent legislation and Executive Orders, such as the Federal Water Pollution Control Act Amendments of 1977 (PL 95-217, 33 U.S.C 1323 et seq., "the Clean Water Act"), and Executive Order 12088 ("Federal Compliance with Pollution Control Standards," 13 October 1978), placed the responsibility for compliance with local and state pollution abatement laws with directors of Federal agencies. Corps policies and authorities relative to water quality are contained in ER 1130-2-334, ER 1105-2-50, and EP 1165-2-1.

b. Early reservoir water quality assessment activities were based on techniques and referenced processes commonly accepted in standard limnology and sanitary engineering. However, previous approaches to assessing and solving reservoir water quality problems were sometimes found to be lacking due to processes and water control operations inherent to reservoirs. Some of these water quality problems interfere with project purposes and/or result directly from water control (reservoir regulation) practices. Many of these problems were addressed by the Environmental and Water Quality Operational Studies (EWQOS) research program, and new technologies pertinent to reservoir water quality have been developed. Much of the material in this manual is a product of this program and of field experience from Corps district and division offices.

Section II. Water Quality Assessment in Water Quality Control Management

1-5. General. Water quality assessments of reservoirs are designed and conducted to meet specific reservoir use objectives. These assessments are intended either for predicting future conditions, such as the reservoir water quality in a proposed impoundment or the tailwater quality resulting from proposed changes in the water control plan at an existing project, or for describing existing conditions, such as postimpoundment quality. In addition, the results of water quality assessments serve as source material for environmental impact statements and assessments, project water control manuals, recreation master plans, and future projects.

1-6. Planning and Analysis. The stage of the reservoir project investigation determines the extent of resources available and, therefore, the depth of a water quality assessment. Obviously, a reservoir water quality assessment made during the early stages of a project reconnaissance investigation is generally less intensive and definitive than assessments conducted during feasibility studies or those made for project feature design and environmental impact determination in the post-authorization phase.

a. Reconnaissance Studies.

(1) During the early phases of project planning investigations (reconnaissance), it is important to make an initial information search (Chapter 4, para 4-3) and determine existing water quality conditions in the watershed under study. Factors such as elevated levels of certain water quality constituents, municipal and industrial point-sources of pollution, land use practices, municipal water supply requirements, State stream water quality standards, and other water uses should be identified. These factors are extremely important in determining water quality assessment requirements and objectives for the next phase of the planning investigation.

(2) Limited resources and the fact that specific reservoir sitings and project purposes are not yet fully developed during the reconnaissance phase usually preclude the need for extensive field data collection or use of the diagnostic and predictive techniques described in Chapter 4.

(3) When the planning investigation progresses to the point at which alternative reservoir sites are considered, the process of assessing future reservoir water quality conditions begins. Usually, resources at this stage permit only limited field data collection. Predictive techniques will also ordinarily be restricted to the use of regression type and/or comparative type analyses (Chapter 4). The requirements at the stage of study are to provide a general indication of the proposed impoundment in terms of whether it will be strongly stratified, will have low dissolved oxygen or other gas

concentrations, and related water quality problems that would adversely affect project purposes or require special water control features (e.g., multilevel withdrawal structure or reaeration facility) for mitigation and control. This information will be used to scope the level and extent of the water quality assessment needed for the feasibility investigation.

b. Feasibility Studies.

(1) During the feasibility investigation (development of the recommended plan and preparation of the environmental impact statement), it may be necessary to use nutrient loading, thermal simulations, and/or comprehensive water quality models to predict future water quality and determine the need for specific water quality control features. In most cases, use of rigorous simulation models will require more water quality data than those gathered during the earlier planning work, and additional data collection and analysis will be required.

(2) Another analysis is to determine whether the proposed impoundment lands, through the presence of vegetation and certain soil types, will contribute to water quality degradation (see Chapter 4). Sufficient resources to conduct these water quality studies should be provided in the feasibility investigation. Also, the water quality control features and their associated operational requirements must be considered in the investigation so that accurate estimates of project costs and benefits can be made.

c. Post-authorization Studies. During the post-authorization phase, detailed design of project features and definitive environmental impact determinations are prepared. Resources must be programmed to conduct data collection, while water quality simulation studies may be conducted to select the type and determine the specific geometry of water control structures (e.g., gates, submerged weirs, stilling basins) to meet project purposes and water quality objectives. The studies during this stage will usually encompass use of the more rigorous water quality simulation models (Chapter 4). They may, in addition, require physical models to define project-specific hydrodynamic conditions in the reservoir and tailwater for subsequent use in mathematical models and/or for direct application to design. Guidance on hydrologic investigation requirements for water quality control is contained in ER 1110-2-1402.

1-7. Water Control Management.

a. Water quality assessments of existing reservoirs can vary in completeness and detail depending on the objective of the assessment. For compliance with ER 1130-2-334, it may be sufficient to carry out a monitoring program without resorting to modeling (especially when no water quality problems are identified at the reservoir). In this instance, trend-monitoring to identify possible problems/conditions may be the activity required.

b. For a reservoir in which a specific water quality condition has been identified or to which a change in project use is proposed (e.g., hydropower retrofit), the assessment may be as extensive as that used in post-authorization design studies. In this case, there may be need for extensive field sampling and laboratory analysis (Chapter 5) and for evaluation techniques such as mathematical and/or physical modeling. Further, correcting a water quality problem or meeting requirements of the new project purpose may require the design and construction of modifications to the outlet works and/or modifications to the water control plan.

CHAPTER 2

WATER QUALITY PARAMETERS

Section I. Introduction

2-1. Definition of Water Quality. Water quality, as defined in this manual, is composed of the physical, chemical, and biological characteristics of water and the abiotic and biotic interrelationships.

2-2. Reservoir-Watershed Relationship.

a. Any reservoir or stream system is coupled with its watershed or drainage basin. Therefore, basin geometry, geology, climate, location, and land use are integral factors that directly or indirectly influence stream or reservoir water quality. Conversely, water quality changes in reservoirs are the result of physical, chemical, and biological loading, generally through runoff and/or stream transport and processing.

b. In a dam/reservoir project area, the Corps owns a limited quantity of the surrounding land. As a result, the water quality of a particular reservoir is often controlled by a watershed, and/or activities therein, over which the Corps has little or no control. In turn, many water quality problems in the reservoir cannot be dealt with directly but must be handled by or through a local, state, or other Federal entity. However, one should not assume that all water quality problems are the result of the watershed characteristics alone. Many water quality problems result from structures associated with the dam, project operation, or the reservoir itself. Solutions to these problems are within the control of the Corps.

Section II. Reservoir Description

2-3. Definition. In limnological terminology (study of freshwater bodies), reservoirs are defined as artificial lakes. All standing waters were classified as lakes as far back as the 1890's by the pioneer limnologist Forel. More recently, lakes have been classified into 76 types, with reservoirs as one type of lake produced by higher organisms, that is, man (see Ref. 77).

2-4. Comparison to Natural Lakes. In some ways, reservoirs can be considered as having the characteristics of only one-half of natural lakes. That is, the deepest portion of a natural lake may be located anywhere, but is often near the center, with all portions of the lake bottom sloping toward that maximum depth. By contrast, the deepest portions of reservoirs are almost always near the dam, and the reservoir bottom usually slopes toward the dam. Also, the inlet and outlet of natural lakes are near the surface, whereas a reservoir can release water from any location, ranging from the surface to the deepest portion of the impoundment. Consequently, although the limnological processes determining water quality conditions are the same in both cases, the hydrodynamics of reservoirs make their water quality characteristics different than those of natural lakes. From an ecological point of view, a reservoir normally has variable productivity potential levels--high in the early years, low during the following years and then, sometimes, high again during the reservoir's mature stage. By contrast, the natural lake follows a successional pattern from oligotrophy to eutrophy.

2-5. Classification of Reservoirs. Reservoirs, especially natural lakes, have been classified using a variety of systems, including physical, chemical, and geomorphological characteristics, and indicator species or species aggregates. This section presents a brief overview of the classification systems commonly used within the Corps.

a. Stratified Versus Unstratified. Reservoirs may or may not stratify, depending on conditions such as depth, wind mixing, and retention time (see para 2-7d). Under appropriate conditions, the reservoir will form an epilimnion or upper layer, a metalimnion or transitional layer, and a hypolimnion or lower layer. However, if conditions do not allow stratification, the entire reservoir may consist of an epilimnion with an isothermal gradient. The stratified or unstratified condition can dramatically affect water quality conditions of the reservoir and its releases. Releases from an unstratified reservoir, irrespective of the withdrawal level, will generally be warmwater releases; bottom-level withdrawals from a stratified reservoir will be generally coldwater releases. Warm and cold releases, in the sense of this discussion, are relative to the water temperature of the stream into which the releases are made. Additional aspects of water quality conditions associated with stratified or unstratified conditions will be discussed in subsequent sections.

b. Operational Characteristics.

(1) General. Reservoir projects are authorized for a variety of purposes, the most common of which are flood control, navigation, hydroelectric power generation, water supply, fish and wildlife conservation and enhancement, recreation, and low-flow augmentation. Since the mid-1970's, Corps reservoirs also have water quality enhancement as an authorized project purpose. Today, most reservoirs are authorized as multiple-purpose projects, with storage allocated for two or more purposes. Multiple-purpose reservoirs, operated either separately or as a system, often result in conflicting uses for reservoir storage.

(2) Flood control. Use of a reservoir for flood control consists of storing water in excess of the downstream channel capacity (damaging flows) during flood periods for later release during periods of flow at or below channel capacity (nondamaging flows) at a downstream control point. Since a major factor in flood control reservoirs is maintaining available volume (i.e., empty storage space) for flood storage, the flood control purpose generally is the least compatible with other project purposes.

(3) Navigation. Reservoir projects operated for navigation purposes are directed at providing sufficient downstream flow to maintain adequate water depth for navigation and/or providing sufficient water volume for lockages. In many navigation projects, the reservoir pool is a part of the channel, so pool levels must be controlled to provide both sufficient navigation depths within the pool and downstream depths. Downstream releases for navigation purposes may have a distinct seasonal pattern, with higher releases required during the dry season.

(4) Hydroelectric power generation.

(a) Hydroelectric power generation consists of passing water through turbines to produce electricity. Hydroelectric facilities normally are operated to produce two types of power: baseload power and peak power. Baseload power is firm power generated to supply a portion of a constant daily demand for electricity. Peaking power is power supplied above the baseload to satisfy variable demands during periods of heavy electricity usage. Reservoir releases to meet baseload power are generally constant over several hours, while those designed for peaking power will fluctuate by the hour.

(b) The power output of a facility is determined by the flow through the turbine and the head or pressures exerted on the turbine. Therefore, it is advantageous to have hydroelectric power reservoirs at maximum storage or full pool for maximum power generation. This is best accomplished by pumped-storage hydropower reservoirs which maintain a full pool by pumping previously released water back into the reservoir following generation. Electricity is generated and used during high-demand periods (i.e., high market value) to provide energy to consumers; it is used to pump water back into the reservoir during low-demand periods when energy costs are lower. Most hydroelectric power plants are part of either an interconnected system or a power grid so that flexibility in coordinating generation releases with other water uses is possible.

(5) Water supply. Reservoirs with water supply objectives store water during periods of excess inflow for use during other periods. Withdrawal may take place directly from the reservoir, or in downstream reservoir releases. Water is generally provided to municipal, industrial, or agricultural users as reservoir storage rather than by contract to supply a specific volume of water. Consequently, water supply can be obtained by a user from the reservoir as long as there is sufficient water in that particular segment of storage. Adequate reserve storage is usually maintained to avoid water shortages during drought periods.

(6) Fish and wildlife conservation and enhancement. Reservoirs used for fish and wildlife conservation and enhancement may include features such as intake structures to minimize entrapment and entrainment of fish and other aquatic species; outlet and emergency spillway structures to minimize contact of aquatic species with waters supersaturated with dissolved gases and to provide appropriate release water quality; and fish ladders, fish bypasses, an

other pertinent facilities to permit fish passage around structures. Fish and wildlife habitat at these reservoirs is improved by retaining standing vegetation during construction, as well as providing conditions conducive to growth of suitable aquatic and wetland vegetation.

(7) Recreation. Recreation activities in and around reservoir projects include camping, picnicking, fishing, pleasure boating, water skiing, swimming, and hunting. Similar activities also take place downstream of the reservoir in and adjacent to the tailwater. Recreational users of both areas generally prefer constant water levels.

(8) Low-flow augmentation. Low-flow augmentation reservoirs provide releases that increase flow in the downstream channel for downstream fish and wildlife purposes or for downstream water quality control. Storage allocation for downstream water quality control currently can be obtained only under special circumstances.

c. Trophic Status.

(1) Reservoirs are commonly classified or grouped by trophic or nutrient status. The natural progression of water bodies through time is from an oligotrophic (i.e., low nutrient/low productivity) through a mesotrophic (i.e., intermediate nutrient/intermediate productivity) to a eutrophic (i.e., high nutrient/high productivity) condition. The prefixes "ultra" and "hyper" are sometimes added to oligotrophic and eutrophic, respectively, as additional degrees of trophic status. The tendency toward the eutrophic or nutrient-rich status is common to all impounded waters.

(2) The eutrophication or enrichment process has received considerable study because:

(a) It can be accelerated by nutrient additions through cultural activities (e.g., point-source discharges and nonpoint sources such as agriculture, urbanization, etc.).

(b) Water quality conditions associated with eutrophication may not be desired.

(c) To a certain degree, cultural eutrophication impacts are reversible.

(3) The majority of reservoir water quality conditions relate to the eutrophication process. Certain physical, chemical, and biological factors change during eutrophication (Table 2-1). Quantitative criteria for these factors have been developed to define various trophic states, but the ranges are broad and may not reflect geographic/demographic differences in water quality. (Additional discussion of eutrophication can be found in Refs. 43, 44, 45, and 110 and in Item ff of Appendix B.)

TABLE 2-1

Selected Trophic Indicators and Their Response to Increased Eutrophication[1]

Physical	Chemical	Biological
Transparency (D) (Secchi disk depth)	Nutrient concentrations (I) (e.g., at spring maximum)	Algal bloom frequency (I)
Suspended solids (I)	Chlorophyll *a* (I)	Algal species diversity (D)
	Conductivity (I)	Littoral vegetation (I)
	Dissolved solids (I)	Zooplankton (I)
	Hypolimnetic oxygen deficit (I)	Fish (I)
	Epilimnetic oxygen supersaturation (I)	Bottom fauna (I)
		Bottom fauna diversity (D)
		Primary production (I)
		Phytoplankton biomass (I)

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[1] (I) = Increased, (D) = decreased.

Section III. Reservoir Characteristics and Processes

2-6. General.

a. Reservoir water quality is a system response to the reservoir's watershed, the region's climate, as well as the geometry and internal characteristics and processes of the reservoir. Water quality is affected by the type, location, and manner of operation of the reservoir's water control facilities. Macro- and micro-meteorological forces, inflows, internal processes, outflows, and project operation are highly dynamic and can be dominant factors in determining the water quality in a reservoir. To understand why certain water quality conditions develop, one must understand the interaction of all the dynamic phenomena influencing the reservoir and its associated waters.

b. This section introduces some of the important characteristics and processes that influence the quality of water in reservoirs. For simplicity, relevant limnological factors are categorized as being physical, chemical, or biological in nature. Such separation does not occur in nature; the factors are all interrelated. Thus, it must be understood that many factors discussed could fall into more than one category. (Additional information on limnological processes and terminology can be found in Refs. 77, 78, and 110.)

2-7. Physical Characteristics and Processes.

a. Site Preparation. Depending upon the planned reservoir uses, site preparation (e.g., topsoil stripping, timber removal) may have a significant effect upon water quality after inundation. Additional information on the subject may be found in Refs. 13 and 71.

b. Morphometry.

(1) Morphometric variables that can influence hydrologic and limnologic characteristics of the reservoir include surface area, volume, mean depth, maximum depth, shoreline development ratio, and fetch. Formulas for computing the values of these and other characteristics are given in Table 2-2. Biological productivity, respiration, decomposition, and other processes influencing water quality are related directly or indirectly to reservoir morphometry. Morphometric characteristics themselves also are interrelated and provide insight into existing or potential water quality conditions. Mean depth, for example, is computed as volume/surface area (V/A); shallow mean depths may indicate light penetration to the bottom, warmer water temperatures, higher organic decomposition rates, and greater nutrient regeneration. All these factors can contribute to higher productivity. Lakes with shallow mean depths generally have higher biological productivity than lakes with deeper mean depths with comparable surface areas.

TABLE 2-2

Physical, Chemical, Morphometric, and Hydrologic Relationships*

Characteristics	Symbol	Formulation	Reference No.
Physical			
Water Density	ρ_w	$\rho_T + \Delta\rho_{TDS} + \Delta\rho_{SS}$	
- Thermal	ρ_T	$1,000 - \frac{(T - 3.98)^2 (T + 283)}{(503.57)(T + 67.26)}$	
- Total Dissolved Solids Increment	$\Delta\rho_{TDS}$	$\sim 0.00078 * C_{TDS}$	
- Suspended Solids Increment	$\Delta\rho_{SS}$	$\sim 0.00062 * C_{SS}$	
Settling Velocity (Stokes Law)	v_s	$\frac{gD^2}{18\nu} (\rho_s - \rho)$	106
Viscosity	ν	$\rho(0.069\ T^2 - 5.3T + 177.6)$	96
Sedimentation Index	S_I	$\tau(QL/V)$	75
Areal Erosion	$a_E + T$	$1,090\sqrt{A}/Z * \exp\ (Z/\sqrt{A})$	72

(Continued)

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* Symbols used in this table are defined in Appendix D.

(Sheet 1 of 4)

TABLE 2-2 (Continued)

Characteristics	Symbol	Formulation	Reference No.
Morphometric/Hydrologic (Collated)			
Drainage Area	DA	-	
Surface Area (Normal Pool)	A	-	
Volume (Normal Pool)	V	-	
Length (Normal Pool)	L	-	
Maximum Depth (Normal Pool)	Z_m	-	
Outlet Elevation	Z_C	-	
Normal Pool Elevation	Z_n	-	
Spillway Elevation	Z_s	-	
Shoreline Length	L_s	-	
Morphometric/Hydrologic (Calculated)			
Mean Depth	$\overline{Z}$	V/A	
Development of Volume	Z/Z_m	-	
Mean Breadth	$\bar{b}$	A/L	110
Drainage Area/Surface Area Ratio	DA/SA	-	

(Continued)

(Sheet 2 of 4)

Table 2-2 (Continued)

Characteristics	Symbol	Formulation	Reference No.
Morphometric/Hydrologic (Calculated) (Cont.)			
Shoreline Development Ratio	D_L	$\frac{L_s}{2\sqrt{\pi A}}$	110
Mean Hypolimnion Depth	Z_H	$Z(1 - Z_T/Z_m)$	107
Relative Depth	Z_r	$\frac{50\ Z_m \sqrt{\pi}}{\sqrt{A}}$	110
Hydraulic Residence Time	τ	V/Q	
Flushing Rate	α	$1/\tau$	32
Single Storm Flushing Rate	β	Q_s/V	32
Areal Water Load	q_s	Q/A	
Densimetric Froude Number	F_d	$320 * \frac{LQ}{ZV}$	32
Plunge Point Depth	D_p	$\left(\frac{1}{F_p}\right)^{1/3}\left[Q^2/\left(W^2 \cdot g \cdot \frac{\Delta\rho}{\rho}\right)\right]^{1/3}$	67

(Continued)

(Sheet 3 of 4)

Table 2-2 (Concluded)

Characteristics	Symbol	Formulation	Reference No.
Chemical			
Dissolved Oxygen Saturation	DO_{sat}	$DO_{sat} = \exp(7.7117 - 1.31403 * \ln(T + 45.93) + 5.25 * \ln(1 - h/44.3))$	89
Oxygen Supply	T_{DO}	$T_{DO} = DO_i * Z_H/\Delta HOD$	107
Un-ionized Ammonia	NH_3^{UI}	$NH_3^{UI} = \left[1 + 1/\ln^{-1}(0.09019 + 2{,}729.92/T_d - pH_d) * C_e^T Q_e + C_u^T Q_u /Q_e + Q_e\right]$	112
Nitrogen Supersaturation Potential	N_f	See ETL 1110-2-239	
Total Dissolved Solids	TDS	TDS ≈ -0.6 * Specific Conductance	
Soluble Reactive Phosphorus	SRP	SRP ~ (0.4 to 0.5) * TP	34

(Sheet 4 of 4)

(2) Reservoirs with high shoreline development ratios are indicative of dendritic systems with many coves and embayments, while low values of the ratio are often indicative of more prismatic type reservoirs. Biological productivity usually is higher in coves than in the main pool; thus, reservoirs having high shoreline development ratios tend to be more productive.

(3) Fetch is the distance over water that the wind has blown uninterrupted by land. When computed along the direction of the prevailing wind, the fetch length can provide an indication of wave heights and potential erosion areas on the windward reservoir side where the waves will break.

(4) The shape of area-capacity curves integrates morphometric parameters that relate to biological productivity. Reservoirs with flatter slopes on the area-elevation, elevation-volume curves usually have higher productivity.

c. Longitudinal Gradients. Reservoirs can exhibit pronounced longitudinal and vertical physical, chemical, and biological gradients. Long, dendritic reservoirs, with tributary inflows located a considerable distance from the outflow and unidirectional flow from headwater to dam, develop gradients in space and time. Although these gradients are continuous from headwater to dam, three characteristic zones result: a riverine zone, a zone of transition, and a lacustrine zone (Figure 2-1).

(1) Riverine zone. The riverine zone is relatively narrow, well mixed, and although water current velocities are decreasing, advective forces are still sufficient to transport significant quantities of suspended particles, such as silts, clays, and organic particulates. Light penetration in this zone is minimal and may be the limiting factor that controls primary productivity in the water column. The decomposition of tributary organic loadings often creates a significant oxygen demand, but an aerobic environment is maintained because the riverine zone is generally shallow and well mixed. Longitudinal dispersion may be an important process in this zone.

(2) Zone of transition. Significant sedimentation occurs through the transition zone, with a subsequent increase in light penetration. Light penetration may increase gradually or abruptly, depending on the flow regime. At some point within the mixed layer of the zone of transition, a compensation point between the production and decomposition of organic matter should be reached. Beyond this point, production of organic matter within the reservoir mixed layer should begin to dominate (Figure 2-1).

(3) Lacustrine zone. The lacustrine zone is characteristic of a lake system (Figure 2-1). Sedimentation of inorganic particulates is low; light penetration is sufficient to promote primary production, with nutrient levels the limiting factor; and production of organic matter exceeds decomposition within the mixed layer. Entrainment of metalimnetic and hypolimnetic water, particulates, and nutrients may occur through internal waves or wind mixing during the passage of large weather fronts. Hypolimnetic mixing may be more extensive in reservoirs than lakes because of bottom withdrawal. Bottom

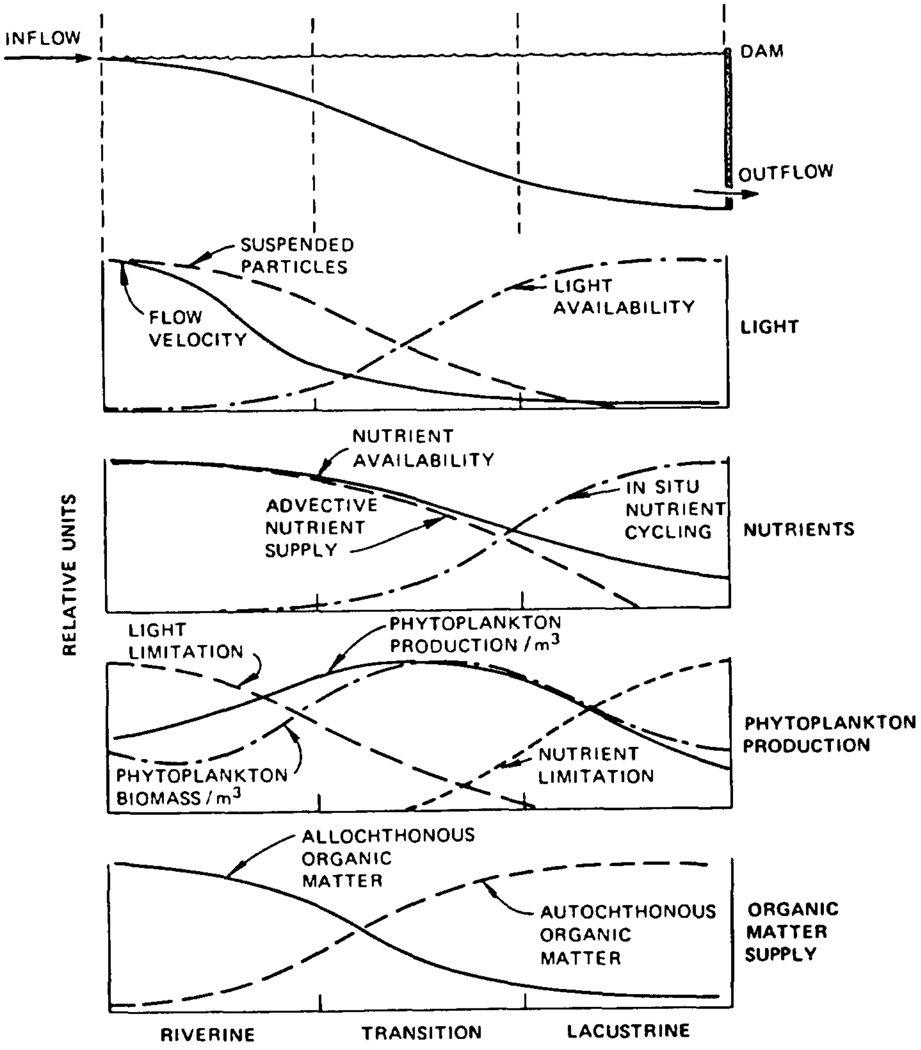


Figure 2-1. Longitudinal patterns in reservoir water quality (after Item y, Appendix B)

withdrawal removes hypolimnetic water and nutrients and may promote movement of interflows or underflows into the hypolimnion. In addition, an intake structure may simultaneously remove water from the hypolimnion and metalimnion.

d. Vertical Gradients. Attaining reservoir water quality objectives can be significantly affected by vertical stratification in the reservoir. This stratification typically occurs through the interaction of wind and solar isolation at the reservoir surface and creates density gradients that can influence reservoir water quality (see Figure 2-2). Stratification also can result from density inflows (see para 2-7i) or high total dissolved solids (TDS) or

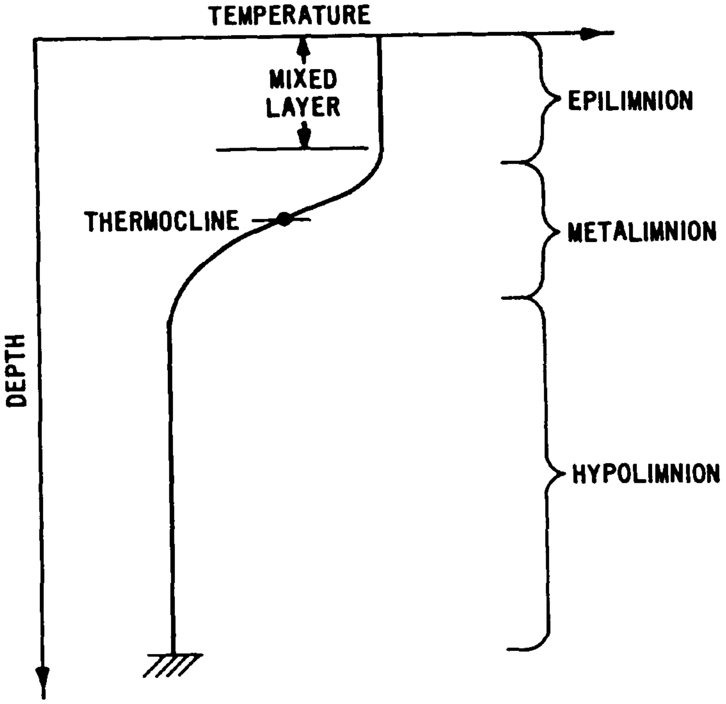


Figure 2-2. Vertical zonation resulting from thermal stratification

suspended solids (SS) concentrations. Because of density stratification and its sensitivity to meteorological conditions and tributary inflows, proper hydraulic outlet design is imperative to ensure that reservoir and release water quality objectives can be met. Reservoir hydraulic outlet designs include the capability for bottom, surface, and multilevel withdrawal; low-flow releases; or the passing of large flows over a spillway.

(1) Bottom withdrawal. Bottom withdrawal structures are located near the deepest part of a reservoir (Figure 2-3). Historically, bottom withdrawal structures have been the most common outlet structures used to release reservoir waters. They release cold waters from the deep portion of the reservoir; however, these waters may be anoxic during periods of stratification. Bottom outlets can release density interflows or underflows (e.g., flow laden with sediment or dissolved solids) through the reservoir and generally provide little or no direct control over release water quality. In order to control release water quality in projects with bottom outlets, external techniques such as release aeration, hypolimnetic aeration, or localized mixing must be used.

(2) Surface withdrawal. Surface withdrawal structures release waters from near the surface of the reservoir pool (Figure 2-4) and include morning

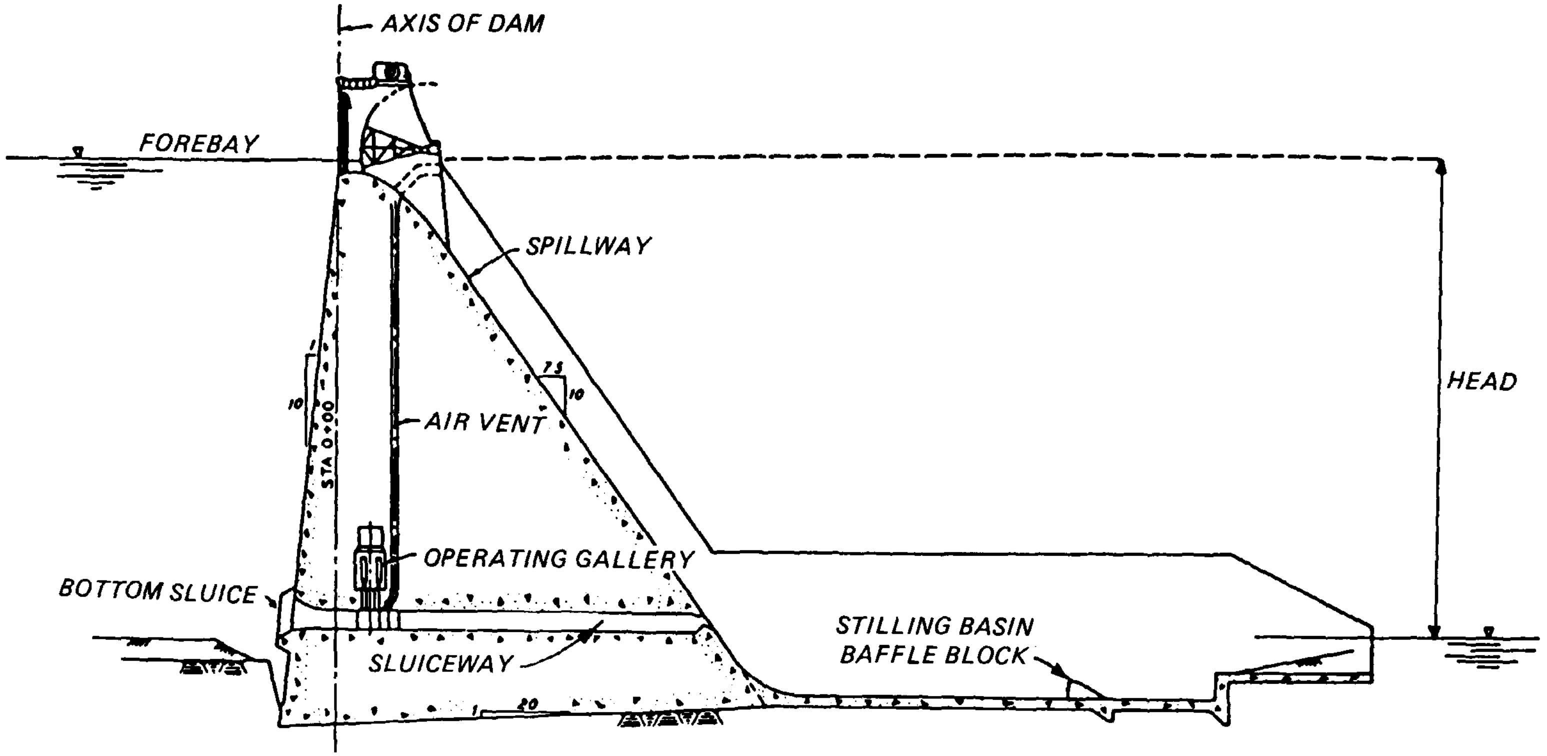


Figure 2-3. Illustration of bottom withdrawal structure, spillway, and stilling basin

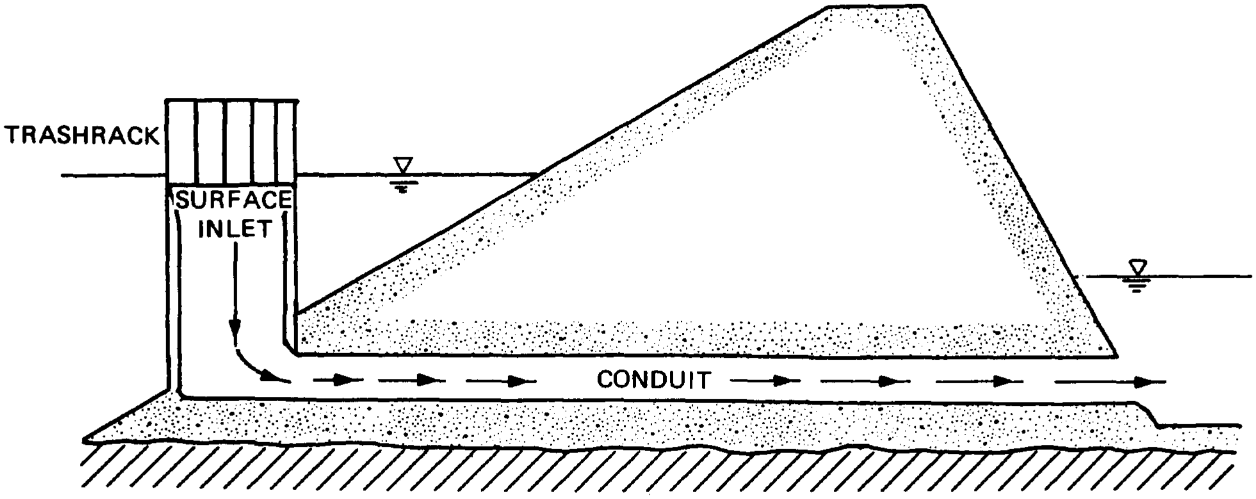


Figure 2-4. Example of surface withdrawal structure

glory, drop inlet siphon, or shaft inlets. Outlet structures at the surface generally release relatively warm, well-oxygenated waters. Surface outlets must be designed to operate within the range of fluctuation of the reservoir water surface. The surface outlet becomes unusable once the reservoir water surface elevation falls below the crest of a surface outlet structure. Density interflows or underflows cannot be released using surface outlets, nor is there any direct control over the water quality of the release using'the outlet structure. Few external techniques for controlling water quality within the reservoir can be used to control the water quality of releases from surface structures.

(3) Multilevel withdrawal. Multilevel withdrawal structures have one or more outlet towers, each containing a number of inlet ports at different elevations (Figure 2-5). This configuration provides the flexibility to release water from several levels within the reservoir. Designing port locations at various elevations may permit reservoir operation to meet release water quality objectives by withdrawing water with the desired quality from appropriate elevations in the reservoir. However, in a single tower, only one port can be effectively operated at any time if the reservoir is stratified. Operating two ports at different elevations simultaneously in a stratified reservoir with a single wet well can result in density blockage of flow, flow instability, pulsating release quality, and overall reduced control over release quality. As a result, a single wet well is not conducive to blending water from different elevations. However, with a system of two or more wet wells, one port in each wet well can be opened to blend waters from different elevations to meet downstream water quality objectives. Multilevel outlets can also be used to pass density flows through reservoirs, but port capacities are generally limited to those capacities used in normal operation. Also, larger

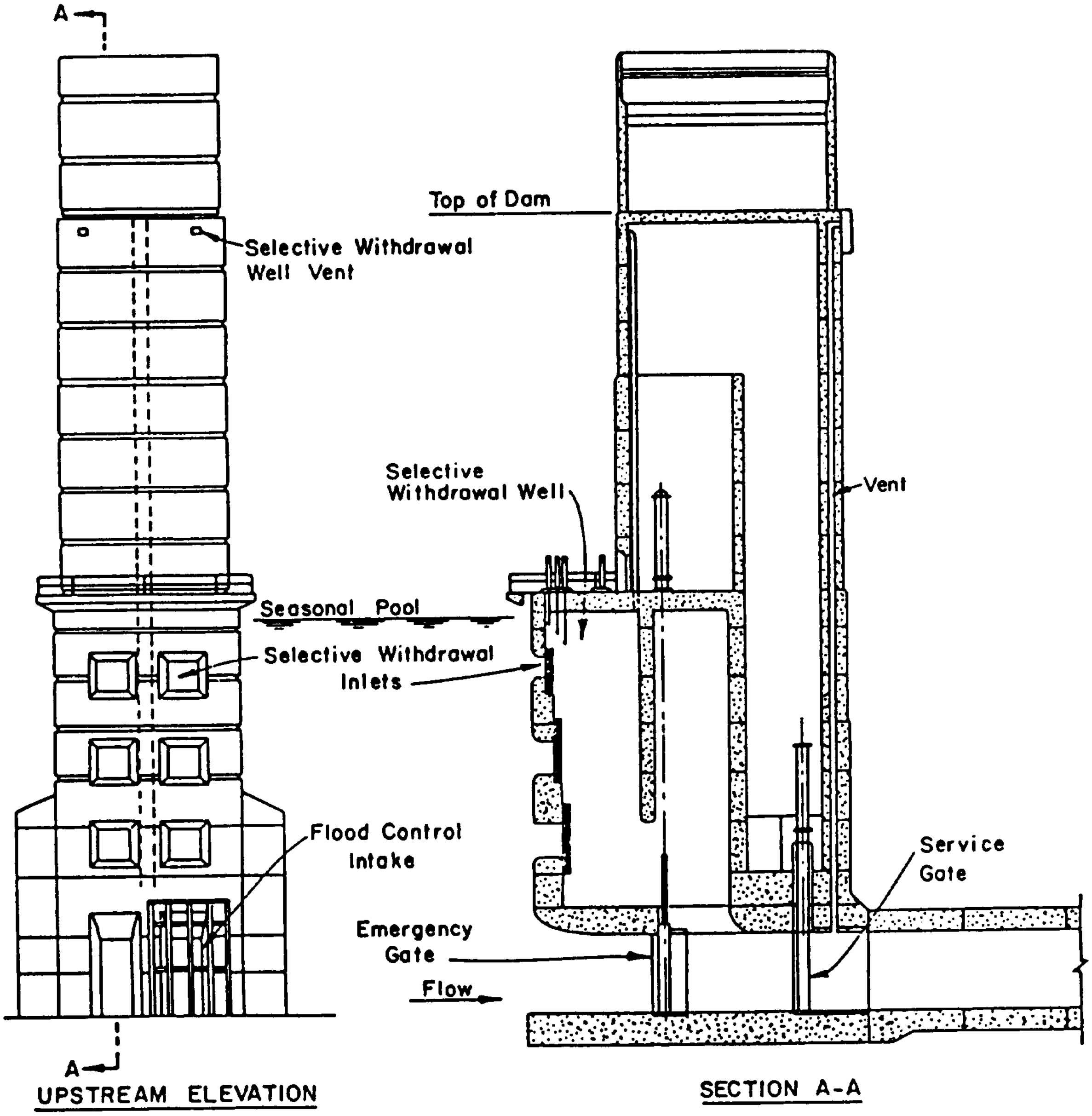


Figure 2-5. Dual wet well multilevel withdrawal structure

flows can be passed by combining a flood control outlet or spillway with the multilevel intake structure. However, using spillway releases and hydropower releases may not result in a uniform downstream quality. Such waters may not readily mix because of density differences. The flood control outlet is commonly a large-capacity bottom outlet. Flood control operation, however, generally results in temporary loss of control over release quality unless nonflood flows also are discharged through the bottom outlet or over the spillway.

e. Water Budget.

(1) The water balance in reservoirs is the result of the income of and losses from the reservoir and can have a significant effect on reservoir and release water quality on an annual, seasonal, daily, and even hourly basis. The income may consist of precipitation on the water surface, tributary inflow, watershed runoff, point source discharges, and ground water. Water losses occur through evaporation from the water surface, evapotranspiration by aquatic plants, reservoir withdrawals, leakage, and ground-water recharge or seepage. The change in water storage is a function of the difference between income and loss.

(2) The total water budget varies from wet year to dry, season to season, and day to day. Any assessment of water quality requires a clear understanding of the project's water budget and the variability of that budget with time. Factors such as chemical concentrations and stratification, turbidity, productivity, thermal regime, and sediment transport are strongly influenced by a project's water budget.

f. Water Properties. Water has several unique physical properties that must be considered in water quality assessment. These properties include density, specific heat, viscosity, and surface tension.

(1) Density. Water has its maximum density, 1 gram per milliliter, near 4° C (Figure 2-6) and is a nonlinear function of temperature. Water becomes less dense or buoyant as the temperature either increases or decreases from 4° C. Ice floats on water, and warmer water floats on cold water because of these density differences. Further, the temperature-density relation is nonlinear; the density difference between 20° and 21° C is approximately equal to the density difference between 5° and 10° C. Density is also significantly influenced by TDS and SS concentrations. Normally, as TDS and SS concentrations increase, so does density. Density differences influence internal reservoir mixing processes, as well as water quality.

(2) Specific heat. The specific heat of water is 1.0 kilocalorie per kilogram °C, which is four times the specific heat of air. As a result, water gains or loses heat more slowly than air. Therefore, large changes in daily air temperatures generally elicit much smaller changes in water temperature. The large reservoir water mass and high specific heat of the water

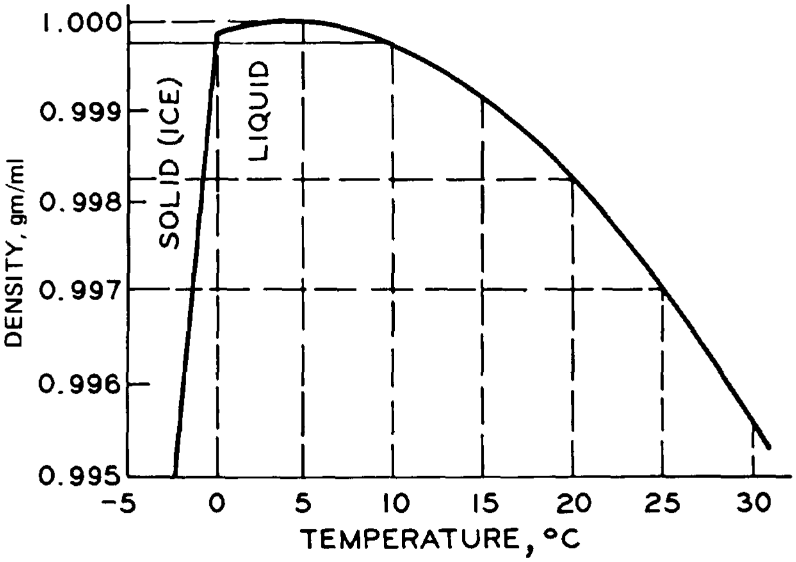


Figure 2-6. Water density as a function of temperature

cause temperatures in reservoirs to increase more slowly in the spring and decrease more slowly in the fall than stream or air temperatures.

(3) Viscosity. Viscosity is the internal fluid resistance, caused by molecular attraction, that makes a fluid resistant to flow and is a function of temperature, decreasing as temperature increases. An illustration of this property is that particulate matter, suspended in the water (i.e., algae, detritus, sediment), will settle faster as temperature increases, since viscosity is lower at higher temperatures.

(4) Surface tension. Surface tension at the air/water interface is caused by unbalanced molecular attractions that exert an inward adhesion to the liquid phase (Ref. 110). Surface tension decreases with increasing temperature. Also, surface tension can maintain the concentration of debris on the surface and form a unique microhabitat for microorganisms. Organic compounds, either naturally produced dissolved organic carbon (DOC) or organic pollutants such as oil, markedly reduce surface tension.

g. Thermal regime. The annual temperature distribution represents one of the most important limnological processes occurring within a reservoir. Thermal variation in a reservoir results in temperature-induced density stratification, and an understanding of the thermal regime is essential to water quality assessment. A brief discussion of the thermal regime of a reservoir in the temperate climate is presented in the following paragraphs.

(1) Spring thermal regime. As the ice cover deteriorates in the spring, the surface water, which is near 0° C, begins to warm and approach the temperature of the bottom water. Since the density of the surface water increases

as it approaches 4° C, this surface water sinks and mixes with the water below it. During this period, there is relatively little thermally induced resistance to mixing because of the small density differences, and the reservoir becomes uniform near 4° C. This period of uniform temperature is referred to as spring turnover. The extent of this period is primarily dependent on inflow density, wind mixing, and solar insolation. Solar insolation warms the surface water and thereby establishes a density gradient between the surface and underlying water. However, wind energy introduced across the water surface stirs the water column and distributes this heat into the water column, resulting in an increase in the temperature of the entire water column to or above 4° C. As solar insolation intensifies, wind energy no longer can overcome the density gradient between the surface and bottom and completely mix the water column. As a result, a temperature gradient is established in the water column, which is called thermal stratification.

(2) Summer thermal regime. During the summer, solar insolation has its highest intensity and the reservoir becomes stratified into three zones (Figure 2-2).

(a) Epilimnion or mixed layer. This upper zone represents the less dense, warmer water in the reservoir. It is fairly turbulent since its thickness is determined by the turbulent kinetic energy (TKE) inputs (wind, convection, etc.), and a relatively uniform temperature distribution throughout this zone is maintained.

(b) Metalimnion. The metalimnion is the middle zone that represents the transition from warm surface water to cooler bottom water. There is a distinct temperature gradient through the metalimnion. The metalimnion in some references is called the thermocline. The thermocline, however, represents the plane or surface of maximum rate of change of temperature in the metalimnion.

(c) Hypolimnion. The hypolimnion is the bottom zone of colder water that is relatively quiescent in lakes. Bottom withdrawal or fluctuating water levels in reservoirs, however, may significantly increase hypolimnetic mixing.

(3) Fall thermal regime. As solar insolation decreases during autumn and the air and inflow temperatures cool, reservoir heat losses exceed heat inputs, and water surface temperatures decrease (Figure 2-7). This results in the surface water becoming denser and mixing with deeper water through wind and convection currents, and a reduction of the density difference between the mixed layer and hypolimnion. This situation results in a deepening of the mixed layer and erosion of the metalimnion. As fall cooling progresses, the water column eventually reaches a uniform temperature. This period of uniform temperature in the water column is called fall turnover.

(4) Winter thermal regime. Thermal uniformity of the water column will continue unless the surface water freezes. Ice formation prevents wind mixing, and inverse stratification may form under the ice. The bottom wate

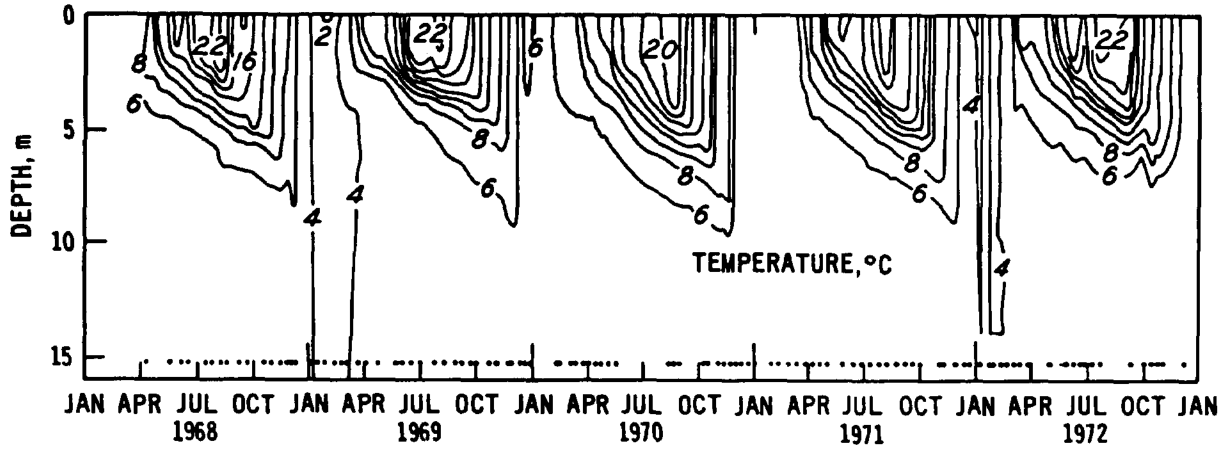


Figure 2-7. Recurring annual stratification pattern for temperate reservoir

or deeper strata may stay near maximum density at 4° C, but the surface waters become colder and less dense and offer resistance to mixing, so an inverse stratification occurs with 0° C water at the surface and 4° C water near the bottom (Figure 2-7).

(5) Exceptions. The above discussion of thermal regimes in reservoirs (paras 2-7g(1)-(4)) is generally applicable, but, as in most phenomena, there are exceptions. One exception is that, although spring and fall turnover usually produce uniform temperature in the vertical, the influence of dissolved and/or suspended constituents can result in the existence of a chemically induced density gradient, particularly in deeper reservoirs. Another exception is that certain inflow and withdrawal conditions, such as bottom withdrawals that deplete the hypolimnion, can greatly alter the density gradient within the pool. As a result, specific characteristics of each reservoir must be considered in any water quality assessment.

h. Other Stratification. Density stratification due to a temperature gradient is the most common type of stratification, but other factors may also produce density differences that result in reservoir stratification. If density differences prevent mixing with the overlying water, the resulting condition is called a meromictic or incompletely mixed system. In meromictic reservoirs, the bottom waters are isolated by a monimolimnion, which is similar to the metalimnion. Density differences may be due to physical, chemical, or biological factors.

(1) Physical. High suspended sediment concentrations may increase fluid densities and provide resistance to mixing. Although suspended solids settle rapidly, fine colloidal particles transported into a reservoir during major storm events can prevent the bottom waters from mixing with the overlying water column until settling, dilution, and entrainment eliminate this condition.

As a consequence, a difference in density between the bottom and overlying water can occur for a period after a major storm event.

(2) Chemical. High TDS or salinity concentrations can increase water density and prevent complete mixing of the system. The gradient between the upper mixed layer and lower dense chemical layer is a chemocline.

(3) Biological. Decomposition of sediments or sedimenting organic matter can result in salt accumulation that increases the density of the bottom waters and prevents mixing. This condition, called biogenic meromixis, may occur during the initial filling and transition period of a reservoir when decomposition of flooded soils and vegetation is intense. However, this type of stratification generally decreases through time.

i. Inflow Mixing Processes. When tributary inflow enters a reservoir, it displaces the reservoir water. If there is no density difference between the inflow and reservoir waters, the inflow will mix with the reservoir water as the inflow parcel of water moves toward the dam. However, if there are density differences between the inflow and reservoir waters, the inflow moves as a density current in the form of overflows, interflows, or underflows (Figure 2-8). Knapp (Ref. 85) provides an excellent qualitative discussion of inflow mixing, while Ford and Johnson (Ref. 12) discuss reservoir density currents and inflow processes.

j. Internal Mixing. Internal mixing is the term used to describe mixing within a reservoir from such factors as wind, Langmuir circulation, convection, Kelvin-Helmholtz instabilities, and outflow (Figure 2-9). Additional

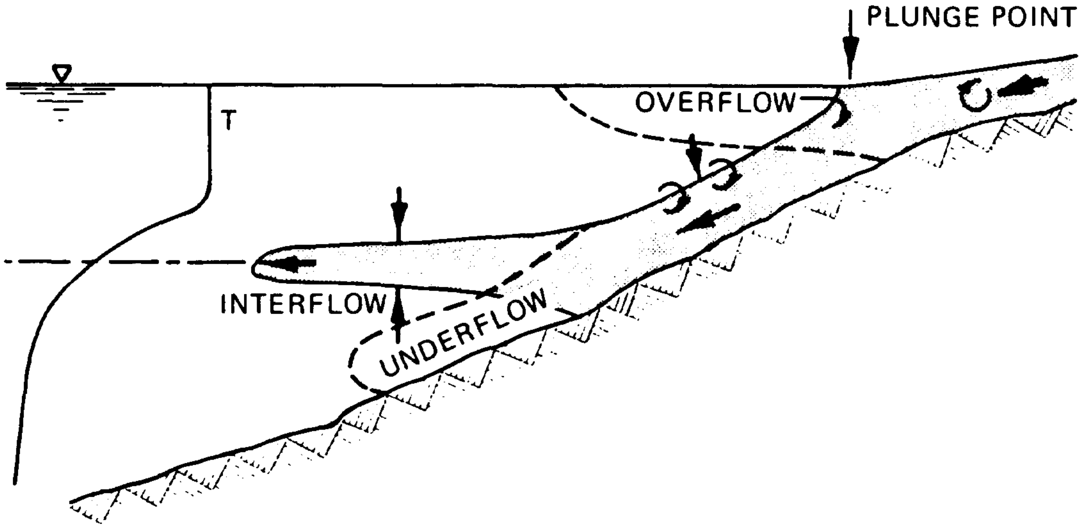


Figure 2-8. Density inflows to reservoirs (after Ref. 12)

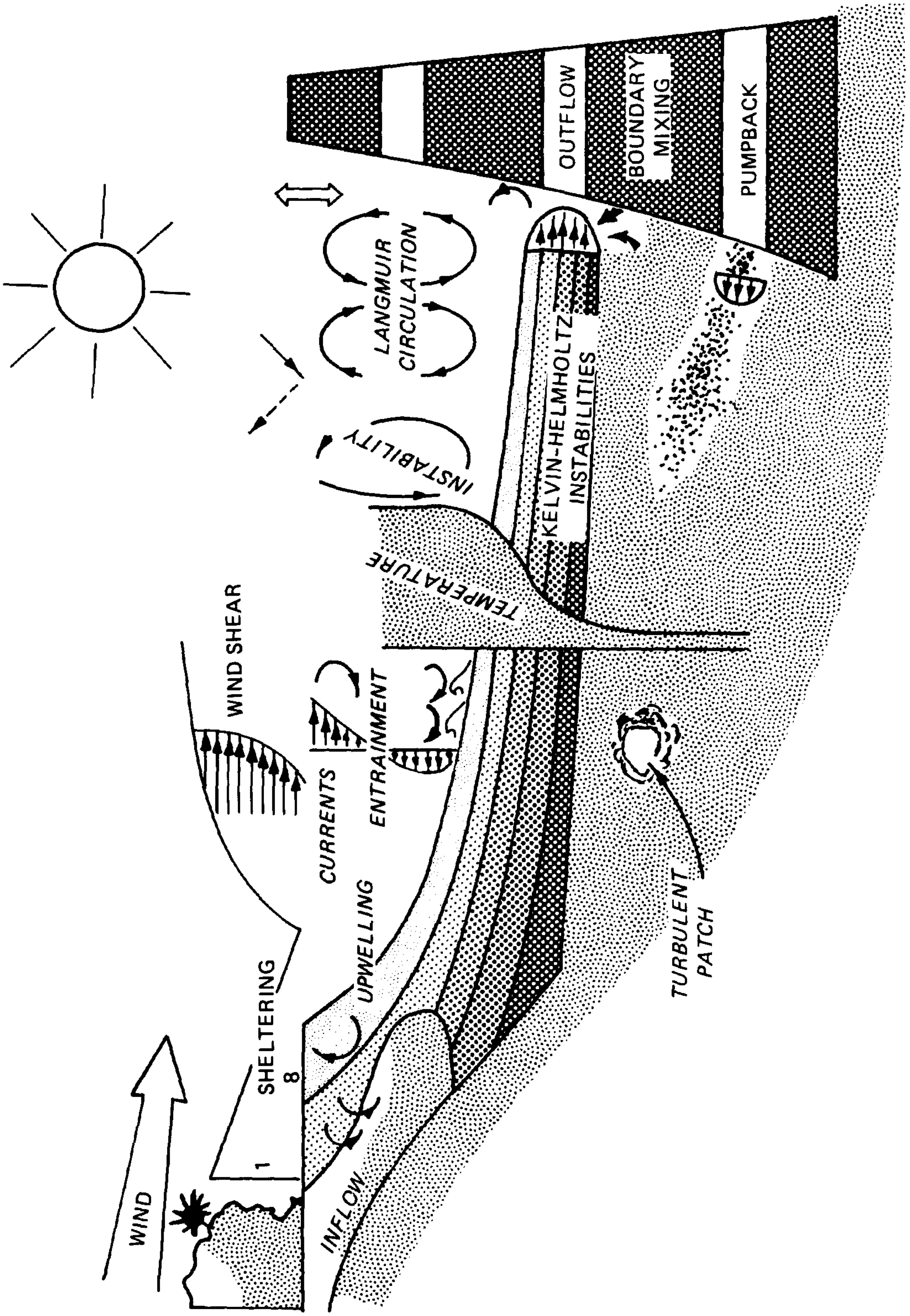


Figure 2-9. Internal mixing processes in reservoirs

topical information is available from the following sources: dynamics of large lakes (Refs. 55 and 89 and Item h); mixing dynamics (Refs. 11, 66, 73, and 81); turbulence (Ref. 103); inflow dynamics (Ref. 12); and outflow dynamics and selective withdrawal (Ref. 80). An excellent reference on the influence of density stratification on mixing and flow is the Proceedings of the Second International Symposium on Stratified Flow (Ref. 57).

(1) Wind mixing. In many lakes and reservoirs, wind is a major energy source for mixing. Mixing results from the interaction and cumulative effects of wind-induced shear at the air/water interface (e.g., currents, surface waves, internal waves, seiches, and entrainment). Wind is highly variable, with seasonal, synoptic, and diel (24-hour) cycles. Synoptic cycles correspond to the passage of major weather systems or fronts and have a period of 5 to 7 days. Wind is an important factor influencing the depth of the mixed layer. Langmuir circulations are wind-induced surface currents that move as vertical helices. Wind energy is converted into turbulence by many different processes, including the direct production of turbulence. This surface turbulence is transported downward and mixes water until the density gradient or thermal resistance to mixing dissipates the energy, resulting in the mixed layer depth.

(2) Convection. Convective mixing results from density instabilities due to cooling of surface waters. As the surface water cools it becomes more dense and settles, mixing with underlying strata. Penetrative convective cooling during the fall can be an important factor in deepening of the mixed layer and erosion of the metalimnion (Figure 2-10).

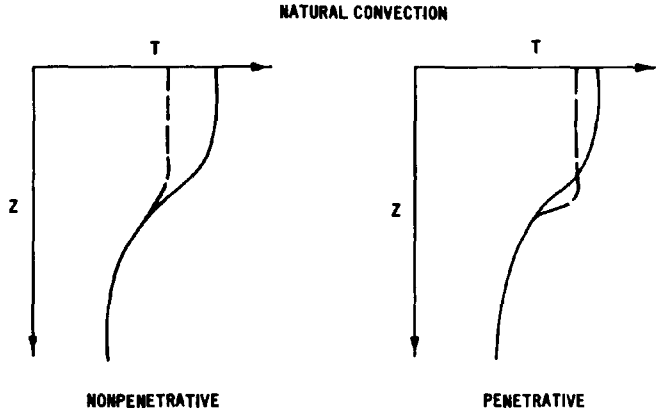


Figure 2-10. Influence of penetrative convective mixing on deepening the mixed layer

(3) Kelvin-Helmholtz instabilities. Internal and surface waves and seiches transport momentum but contribute little mixing unless energy is dissipated through shear or friction. When internal waves become unstable and break, the process is referred to as a Kelvin-Helmholtz instability, and mixing occurs at the interface. Since reservoir operation can result in

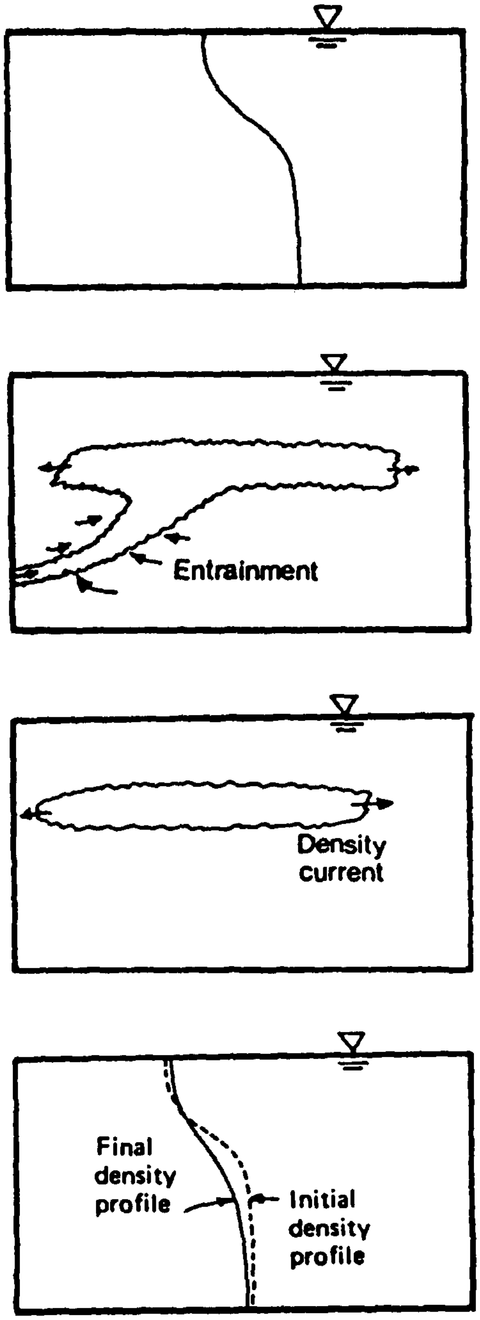
fluctuating water levels and unsteady flow, significant mixing can occur at various interfaces in the reservoir such as the sediment/hypolimnion interface, meta/hypolimnion, and epi/metalimnion interface.

(4) Outflow mixing. When water is released from a reservoir, potential energy is converted into kinetic energy. Mixing is a result of this conversion of energy, although restricted to the zone of outflow, and is proportional to the third power of the discharge. The outflow zone is a function of the stratification regime and the hydraulic outlet geometry and operation (Refs. 7, 22). Hypolimnetic or bottom withdrawal can increase mixing in the hypolimnion and alter the stratification profile in the pool. Hydroelectric power generation can significantly increase mixing in the pool.

k. Pumped Storage. Pumped-storage hydroelectric power operations can increase mixing both through outflow mixing and through mixing and entrainment of the pumpback jet into the reservoir. Depending on the elevation of the inlets, the pumpback jet may move as a density flow entraining the surrounding water until it reaches a level with comparable density (Figure 2-11). This mixing can result in the vertical movement of hypolimnetic constituents into the upper waters.

l. Sediment Dynamics. Sediment deposition patterns and sediment quality, however, markedly influence reservoir water quality. Sediment characterization, yield, transport mechanics, and other aspects of sedimentation engineering (Ref. 106) are important considerations.

m. Deposition Patterns. Gravels, sands, and other coarse sediments are deposited in the reservoir delta and do not influence water quality. The reservoir delta is defined as the deposition zone between the maximum normal flood pool and the normal conservation pool. Suspended sediment transported into the reservoir typically ranges from coarse silts and particulate organic matter to fine clays and colloidal organic matter. As turbulence and river velocities decrease in the reservoir headwater, the sediment-carrying capacity of the river decreases and sediments are deposited. Since the river and its constituent load generally follow the old thalweg through the reservoir, sediment deposition initially is greatest in the old channel. Sedimentation and deposition rates are highest in the headwater and decrease exponentially down the reservoir with plug flow characteristics. This results in a longitudinal sorting of particulate matter by particle size. The coarse silts and organic particles settle in the upper portion of the reservoir; fine silts, coarse clays, and finer organic particles settle next, with the fine clays and colloidal material settling very slowly. Finally, sediment deposition patterns are extremely complex and reflect the interaction of inflow patterns and storage patterns as well as physical, chemical, biological, and seasonal factors that affect the water and the watershed. An example of a typical distribution of deposited particle size in a reservoir is:



a. Initial conditions, typical density stratification

b. Buoyant jetting inflow

c. Shortly after inflow ceases

d. Long time after inflow ceases

Figure 2-11. Important hydrodynamic features of pumped-storage reservoirs subject to jetting inflows (after Ref. 21)

Particle Size	Percent of Deposited Sediment Inlet	 Mid-Reservoir	 Outlet
Sand	5	<1	0
Silt	76	61	51
Clay	19	38	49

n. Quality. Water quality characteristics of the sediment are reflected by the particle size distribution. Coarse organic matter and debris generally settle in the delta with the gravels and coarse sands. River plankton or algae are generally thick-walled species or diatoms that can withstand abrasion during transport in the river but settle rapidly in a lower energy regime. These algae and similar particulate organic matter in the coarse silt size range typically settle in the upper portion of the reservoir. Finer particulate organic matter settles farther downstream in the reservoir, with the colloidal organic matter settling even more slowly. In general, the smaller the particle size, the greater the surface area to volume ratio and the greater the sorptive capacity for transporting adsorbed phosphorus, organic carbon, metals, and contaminants. Clays have a high sorptive capacity while sand has essentially no sorptive capacity. As a result, nutrients, metals, and contaminants may be transported into or through the reservoir adsorbed to the fine silts and clays. Since there is a longitudinal sorting by median particle size diameter, there may also be longitudinal gradients of water quality constituents associated with the sediment.

2-8. Chemical Characteristics of Reservoir Processes.

a. Constituents. Some of the most important chemical constituents in reservoir waters that affect water quality are needed by aquatic organisms for survival. These include oxygen, carbon, nitrogen, and phosphorus. Other important constituents are silica, manganese, iron, and sulfur.

(1) Dissolved oxygen. Oxygen is a fundamental chemical constituent of water bodies that is essential to the survival of aquatic organisms and is one of the most important indicators of reservoir water quality conditions. The distribution of dissolved oxygen (DO) in reservoirs is a result of dynamic transfer processes from the atmospheric and photosynthetic sources to consumptive uses by the aquatic biota. The resulting distribution of DO in the reservoir water strongly affects the solubility of many inorganic chemical constituents. Often, water quality control or management approaches are formulated to maintain an aerobic or oxic (i.e., oxygen-containing) environment. Oxygen is produced by aquatic plants (plankton and macrophytes) and is consumed by aquatic plants, other biological organisms, and chemical oxidations. In reservoirs, the DO demand may be divided into two separate but highly interactive fractions: sediment oxygen demand (SOD) and water column demand.

(a) Sediment oxygen demand. The SOD is typically highest in the upstream area of the reservoir just below the headwater. This is an area of transition from riverine to lake characteristics. It is relatively shallow but does stratify. The loading and sedimentation of organic matter is high in this transition area and, during stratification, the hypolimnetic DO to satisfy this demand can be depleted. If anoxic conditions develop, they generally do so in this area of the reservoir and progressively move toward the dam during the stratification period. The SOD is relatively independent of DO when DO concentrations in the water column are greater than 3 to 4 milligrams per liter but becomes limited by the rate of oxygen supply to the sediments.

(b) Water column demand. A characteristic of many reservoirs is a metalimnetic minimum in DO concentrations or negative heterograde oxygen curve (Figure 2-12). Density interflows not only transport oxygen-demanding material into the metalimnion but can also entrain reduced chemicals from the upstream anoxic area and create additional oxygen demand. Organic matter and organisms from the mixed layer settle at slower rates in the metalimnion because of increased viscosity due to lower temperatures. Since this labile organic matter remains in the metalimnion for a longer time period, decomposition occurs over a longer time, exerting a high oxygen demand. Metalimnetic oxygen depletion is an important process in deep reservoirs. A hypolimnetic oxygen demand generally starts at the sediment/water interface unless underflows contribute organic matter that exerts a significant oxygen demand. In addition to metalimnetic DO depletion, hypolimnetic DO depletion also is important in shallow, stratified reservoirs since there is a smaller hypolimnetic volume of oxygen to satisfy oxygen demands than in deep reservoirs.

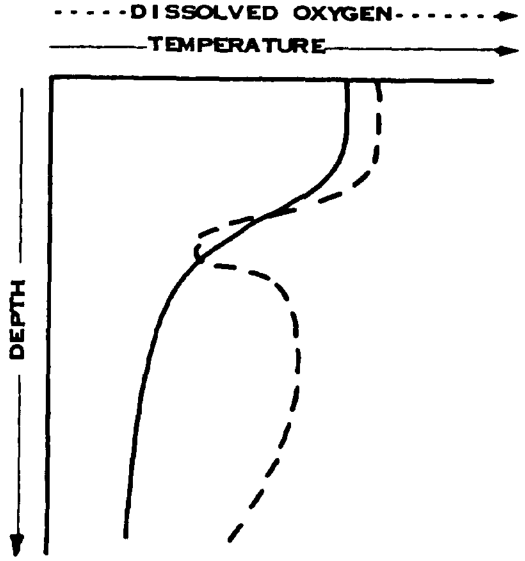


Figure 2-12. Characteristic metalimnetic DO minimum

(c) Dissolved oxygen distribution. Two basic types of vertical oxygen distribution may occur in the water column: an orthograde and clinograde oxygen distribution (Figure 2-13). In the orthograde distribution, oxygen concentration is a function primarily of temperature, since oxygen consumption is limited. The clinograde oxygen profile is more representative of Corps reservoirs where the hypolimnetic oxygen concentration progressively decreases during stratification (Figure 2-13) and can occur during both summer and winter stratification periods.

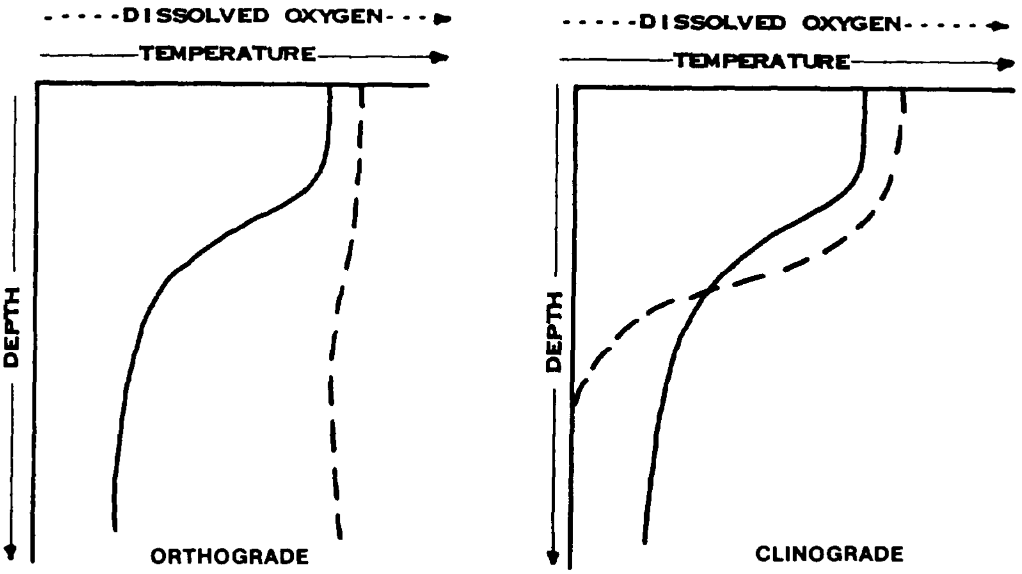


Figure 2-13. Orthograde and clinograde vertical DO distributions

(2) Inorganic carbon. Inorganic carbon represents the basic building block for the production of organic matter by plants. Inorganic carbon can also regulate the pH and buffering capacity or alkalinity of aquatic systems. Inorganic carbon exists in a dynamic equilibrium in three major forms: carbon dioxide (CO_2), biocarbonate ions (HCO_3^-), and carbonate ions ($CO_3^=$). Carbon dioxide is readily soluble in water and some CO_2 remains in a gaseous form, but the majority of the CO_2 forms carbonic acid which dissociates rapidly into HCO_3^- and $CO_3^=$ ions. This dissociation results in a weakly alkaline system (i.e., pH ~ 7.1 or 7.2). There is an inverse relation between pH and CO_2. When aquatic plants (plankton or macrophytes) remove CO_2 from the water to form organic matter through photosynthesis, the pH increases. The extent of this pH change provides an indication of the buffering capacity of the system. Weakly buffered systems with low alkalinities (i.e., <500 microequivalents per

liter) experience larger shifts in pH than well-buffered systems (i.e., >1,000 microequivalents per liter).

(3) Nitrogen. Nitrogen is important in the formulation of plant and animal protein. Nitrogen, similar to carbon, also has a gaseous form. Many species of blue-green algae can use or fix elemental or gaseous N_2 as a nitrogen source. The most common forms of nitrogen in aquatic systems are ammonia (NH_3-N), nitrite (NO_2-N), and nitrate (NO_3-N). All three forms are transported in water in a dissolved phase. Ammonia results primarily from the decomposition of organic matter. Nitrite is primarily an intermediate compound in the oxidation or nitrification of ammonia to nitrate, while nitrate is the stable oxidation state of nitrogen and represents the other primary inorganic nitrogen form besides NH_3 used by aquatic plants.

(4) Phosphorus. Phosphorus is used by both plants and animals to form enzymes and vitamins and to store energy in organic matter. Phosphorus has received considerable attention as the nutrient controlling algal production and densities and associated water quality problems. The reasons for this emphasis are: phosphorus tends to limit plant growth more than the other major nutrients (see Table 2-3); phosphorus does not have a gaseous phase and ultimately originates from the weathering of rocks; removal of phosphorus from point sources can reduce the growth of aquatic plants; and the technology for removing phosphorus is more advanced and less expensive than nitrogen removal.

TABLE 2-3

Nutrient Demand:Supply Ratios During Nonproductive and Productive Seasons[1]

Element	Demand:Supply (range) Late Winter	Demand:Supply (range) Midsummer
Phosphorus	80,000	800,000
Nitrogen	30,000	300,000
Carbon	5,000	6,000
Iron, silicon	Generally low, but variable	
All other elements	Less than 1,000	

[1] After Item ss, Appendix B.

Phosphorus is generally expressed in terms of the chemical procedures used for measurement: total phosphorus, particulate phosphorus, dissolved or filterable phosphorus, and soluble reactive phosphorus (SRP). Phosphorus is a very reactive element; it reacts with many cations such as iron and calcium and is readily sorbed on particulate matter such as clays, carbonates, and inorganic colloids. Since phosphorus exists in a particulate phase, sedimentation represents a continuous loss from the water column to the sediment. Sediment phosphorus, then, may exhibit longitudinal gradients in reservoirs similar to sediment silt/clay gradients. Phosphorus contributions from sediment under anoxic conditions and macrophyte decomposition are considered internal phosphorus sources or loads, are in a chemical form available for plankton uptake and use, and can represent a major portion of the phosphorus budget.

(5) Silica. Silica is an essential component of diatom frustules or cell walls. Silica uptake by diatoms can markedly reduce silica concentrations in the epilimnion and initiate a seasonal succession of diatom species (Ref. 110). When silica concentrations decrease below 0.5 milligram per liter, diatoms generally are no longer competitive with other plankton species.

(6) Other nutrients. Iron, manganese, and sulfur concentrations generally are adequate to satisfy plant nutrient requirements. Oxidized iron (III) and manganese (IV) are quite insoluble in water and occur in low concentrations under aerobic conditions. Under aerobic conditions, sulfur usually is present as sulfate.

b. Gas Exchange.

(1) Gas exchange across the air/water interface is a function of atmospheric pressure, temperature, concentration gradients, and turbulence. The solubility of most gases in water is directly proportional to the partial pressure in the gaseous phase (Henry's Law) and decreases in a nonlinear manner with increasing temperature and altitude (i.e., decreasing atmospheric pressure). Gas transfer is directly proportional to the concentration gradient and turbulence at the air/water interface; however, molecular diffusion is an insignificant mechanism for gas exchange.

(2) Gas exchange across the air/water interface occurs for several gases other than oxygen. Nitrogen, both as elemental nitrogen and ammonia-N, and carbon dioxide also diffuse in and out of the water across this interface. Methane and hydrogen sulfide are two gases that are occasionally produced in the reservoir and may be released across the air/water interface. Water also can, on occasion, become supersaturated with gases. Release of supersaturated gaseous nitrogen, methane, and hydrogen sulfide in reservoir releases can be a major water quality concern in the tailwater.

c. Anaerobic (Anoxic) Conditions.

(1) General. When DO concentrations in the hypolimnion are reduced to approximately 2 to 3 milligrams per liter, the oxygen regime at the sediment/water interface is generally considered anoxic, and anaerobic processes begin to occur in the sediment interstitial water. Nitrate reduction to ammonium and/or N_2O or N_2 (denitrification) is considered to be the first phase of anaerobic processes and places the system in a slightly reduced electrochemical state. Ammonium-nitrogen begins to accumulate in the hypolimnetic water. The presence of nitrate prevents the production of additional reduced forms such as manganese (II), iron (II), or sulfide species. Denitrification probably serves as the main mechanism for removing nitrate from the hypolimnion. Following the reduction or denitrification of nitrate, manganese species are reduced from insoluble forms (e.g., Mn (IV)) to soluble manganous forms (e.g., Mn (II)), which diffuse into the overlying water column. Nitrate reduction is an important step in anaerobic processes since the presence of nitrate in the water column will inhibit manganese reduction. As the electrochemical potential of the system becomes further reduced, iron is reduced from the insoluble ferric (III) form to the soluble ferrous (II) form, and begins to diffuse into the overlying water column. Phosphorus, in many instances, is also transported in a complexed form with insoluble ferric (III) species so the reduction and solubilization of iron also result in the release and solubilization of phosphorus into the water column. The sediments may serve as a major phosphorus source during anoxic periods and a phosphorus sink during aerobic periods (Figure 2-14). During this period of anaerobiosis, microorganisms also are decomposing organic matter into lower molecular weight acids and alcohols such as acetic, fulvic, humic, and citric acids and methanol. These compounds may also serve as trihalomethane precursors (low-molecular weight organic compounds in water; i.e., methane, formate acetate) which, when subject to chlorination during water treatment, form trihalomethanes, or THM's (carcinogens). As the system becomes further reduced, sulfate is reduced to sulfide, which begins to appear in the water column. Sulfide will readily combine with soluble reduced iron (II), however, to form insoluble ferrous sulfide, which precipitates out of solution. If the sulfate is reduced to sulfide and the electrochemical potential is strongly reducing, methane formation from the reduced organic acids and alcohols may occur. Consequently, water samples from anoxic depths will exhibit chemical characteristics.

(2) Spatial variability. Anaerobic processes are generally initiated in the upstream portion of the hypolimnion where organic loading from the inflow is relatively high and the volume of the hypolimnion is minimal, so oxygen depletion occurs rapidly. Anaerobic conditions are generally initiated at the sediment/water interface and gradually diffuse into the overlying water column and downstream toward the dam. Anoxic conditions may also develop in a deep pocket near the dam due to decomposition of autochthonous organic matter settling to the sediment. This anoxic pocket, in addition to expanding vertically into the water column, may also move upstream and eventually meet the anoxic zone moving downstream. (Additional information is provided in Item gg.)

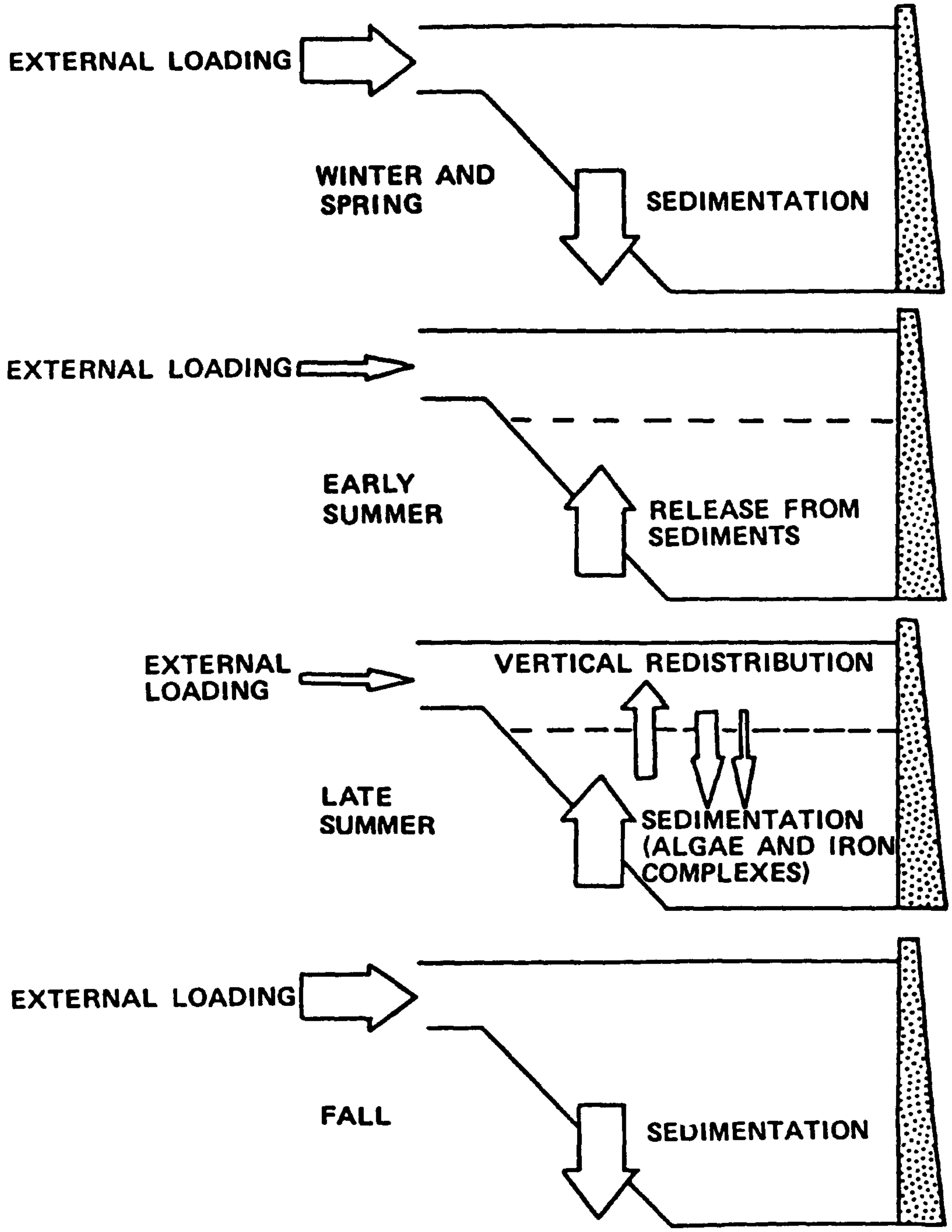


Figure 2-14. Seasonal phosphorus flux under aerobic and anaerobic conditions (after Item x, Appendix B)

(3) Vertical variability. Anoxic conditions are generally associated with the hypolimnion, but anoxic conditions may occur in the metalimnion. The metalimnion may become anoxic due to microbial respiration and decomposition of plankton settling into the metalimnion, microbial metabolism of organic matter entering as an interflow, or through entrainment of anoxic hypolimnetic water from the upper portion of the reservoir.

(d) Initial filling. Reservoirs undergo dynamic chemical and biological changes during the first 6 to 10 years following impoundment. This period following initial inundation has been termed the trophic upsurge period and is generally characterized by increased productivity, although productivity initially may decrease due to high turbidity. The increased productivity is attributed to the rapid decomposition and leaching of organic matter and nutrients from the inundated soil, humus, litter, and herbaceous and woody vegetation. Decomposition and nutrient leaching rates are a function of many variables such as temperature, chemical composition, and cellulose content but are directly proportional to the particle surface area to volume ratio. Pieces of grass, humus, etc., have a larger surface area to volume ratio than limbs and branches. In addition, vegetation high in cellulose, such as standing timber, generally degrades very slowly while grasses and herbaceous vegetation decompose rapidly. Decomposition of this organic material exerts a significant oxygen demand. If the reservoir stratifies, the hypolimnion generally is anoxic for the first several years until this demand is satisfied. The hypolimnetic and release water, then, may contain high concentrations of reduced constituents such as Mn (II), Fe (II), H_2S, and possibly methane. The decline in oxygen demand through time (i.e., 2 to 4 years) is roughly exponential. Decomposition of this organic matter results in high nutrient concentrations, which may stimulate algal production. Benthic productivity also is high during this period since detritus and particulate organic carbon (POC) concentrations are readily available for consumption. Algal and benthic productivity typically result in good fish production during this trophic upsurge period.

2-9. Biological Characteristics and Processes.

a. Meromixis. Decomposition of organic matter in sediments or sedimenting organic matter can increase salinity concentrations, which increases the density of the water and prevents mixing. This condition, called meromixis, may occur during the initial filling and transition period of a reservoir when decomposition of flooded soils and vegetation is intense. This type of stratification generally decreases through time.

b. Microbiological. The microorganisms associated with reservoirs may be categorized as pathogenic (to man and other organisms) or nonpathogenic. Pathogenic microorganisms, including viruses, are of concern from a human health standpoint in that they may limit recreational use. Nonpathogenic microorganisms are important in that they often serve as decomposers of organic matter and are a major source of carbon and energy for a reservoir. Microorganisms generally inhabit all zones of the reservoir (riverine, transition, and lacustrine) as well as all layers (hypolimnion, metalimnion, and epilimnion). Seasonally high concentrations of bacteria will occur during the warmer months but can be diluted by high discharges. Anaerobic conditions enhance growth of certain bacteria while aeration facilitates the use of bacterial food sources. Microorganisms, bacteria in particular, are responsible for mobilization of other contaminants from sediments.

c. Photosynthesis. Oxygen is a by-product of aquatic plant photosynthesis, which represents a major source of oxygen for aquatic ecosystems during the growing season. Oxygen solubility is less during the period of higher water temperatures, and diffusion may be less because wind speeds are usually lower during the summer than the spring or fall. Biological activity and oxygen demand typically are high during stratification, so photosynthesis may represent the major source of oxygen during this period. Oxygen supersaturation in the euphotic zone can occur during periods of high photosynthesis.

d. Phytoplankton and Primary Productivity. Phytoplankton influence DO and suspended solids concentrations, transparency, taste and odor, aesthetics, and other factors that affect many reservoir uses and water quality objectives. Phytoplankton are the primary source of organic matter production and form the base of the autochthonous (i.e., organic matter produced in the system) food web in many reservoirs since fluctuating water levels may limit macrophyte and periphyton production. Phytoplankton species are classified according to standard taxonomic nomenclature but are usually described by general descriptive names such as diatoms, greens, blue-greens, or cryptomonad algae. Phytoplankton species identification and biomass estimates represent static measures of the plankton assemblage, while plankton succession and primary production are dynamic or time-varying measures of the plankton assemblage. Chlorophyll *a* represents a common variable used to estimate plankton biomass while light-dark bottle oxygen measurements or C^{14} uptake are used to estimate primary production. Phytoplankton species in reservoirs are identical to those found in lakes. However, since growth of the phytoplankton is controlled by the physiochemical conditions in reservoirs, the plankton response or spatial variability may vary by reservoir.

e. Temporal Variability. Seasonal succession of phytoplankton species is a natural occurrence in lakes and reservoirs (Figure 2-15). The spring assemblage is usually dominated by diatoms and cryptomonads. Silica depletion in the photic zone and increased settling as viscosity decreases because of increased temperatures usually result in green algae succeeding the diatoms. Decreases in nitrogen or a decreased competitive advantage for carbon at higher pH may result in blue-green algae succeeding the green algae during summer and early fall. Diatoms generally return in the fall but blue-greens, greens, or diatoms may cause algae blooms following fall turnover when hypolimnetic nutrients are mixed throughout the water column. The general pattern of seasonal succession of phytoplankton is fairly constant from year to year. However, hydrologic variability, such as increased mixing and delay in the onset of stratification during wet spring periods, can maintain diatoms longer in the spring and shift or modify the successional pattern in reservoirs.

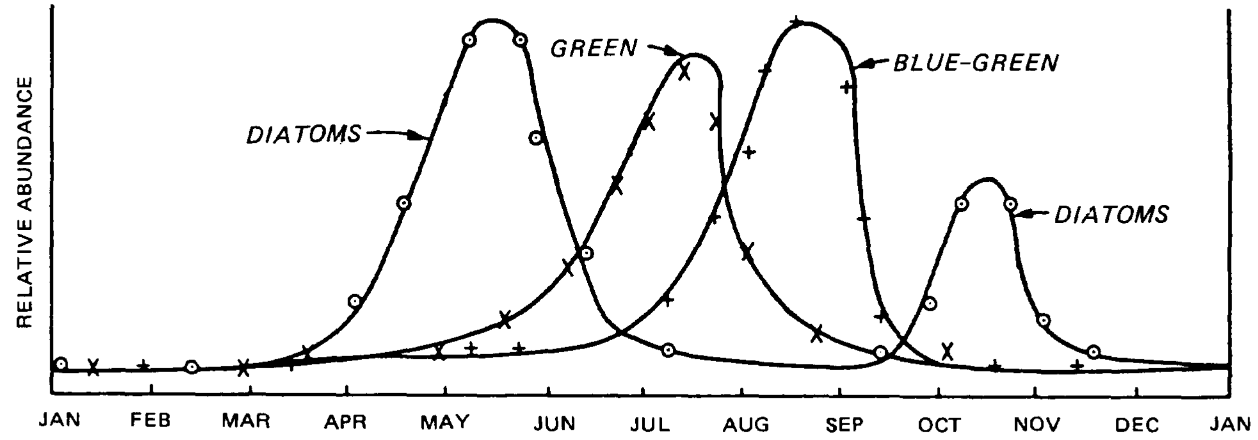


Figure 2-15. Seasonal patterns of phytoplankton succession

f. Macrophytes. Macrophytes or large aquatic plants can be represented by four types of plants: emergent, floating leaved, submerged, or free-floating. Macrophytes generally inhabit the littoral zone or interface zone between the water's edge and the open-water expanse of the reservoir (Figure 2-16). The maximum depth at which attached macrophytes occur is 10 meters, but light penetration generally limits macrophytes to shallower depths. Fluctuating water levels markedly reduce reservoir macrophytes by desiccating and/or freezing the species, although some species are stimulated by fluctuating water levels. Rooted macrophyte species are capable of absorbing nutrients from either the sediment or water column. Since nutrient concentrations are usually greater in the sediment than the water column, sediments represent a major source of nutrients for macrophytes. Nutrients removed from the sediments can be released into the overlying water column as macrophyte tissue decays and can contribute to the internal loading of nutrients in reservoirs. Macrophytes, particularly floating leaved and free-floating species, may compete with phytoplankton for available light. Free-floating species also compete with algae for nutrients. Both free-floating species and algae may limit light so that submersed macrophyte species cannot grow.

g. Periphyton. Periphyton algae grow attached to a substrate such as rocks, sand, macrophytes, or standing timber. Periphyton attached to standing timber in the headwater of reservoirs may serve two functions. First, periphyton may remove nutrients from the inflowing tributary and reduce the nutrients available for reservoir phytoplankton. Second, the periphyton serve as a food resource for the benthos and, directly or indirectly, for fish species.

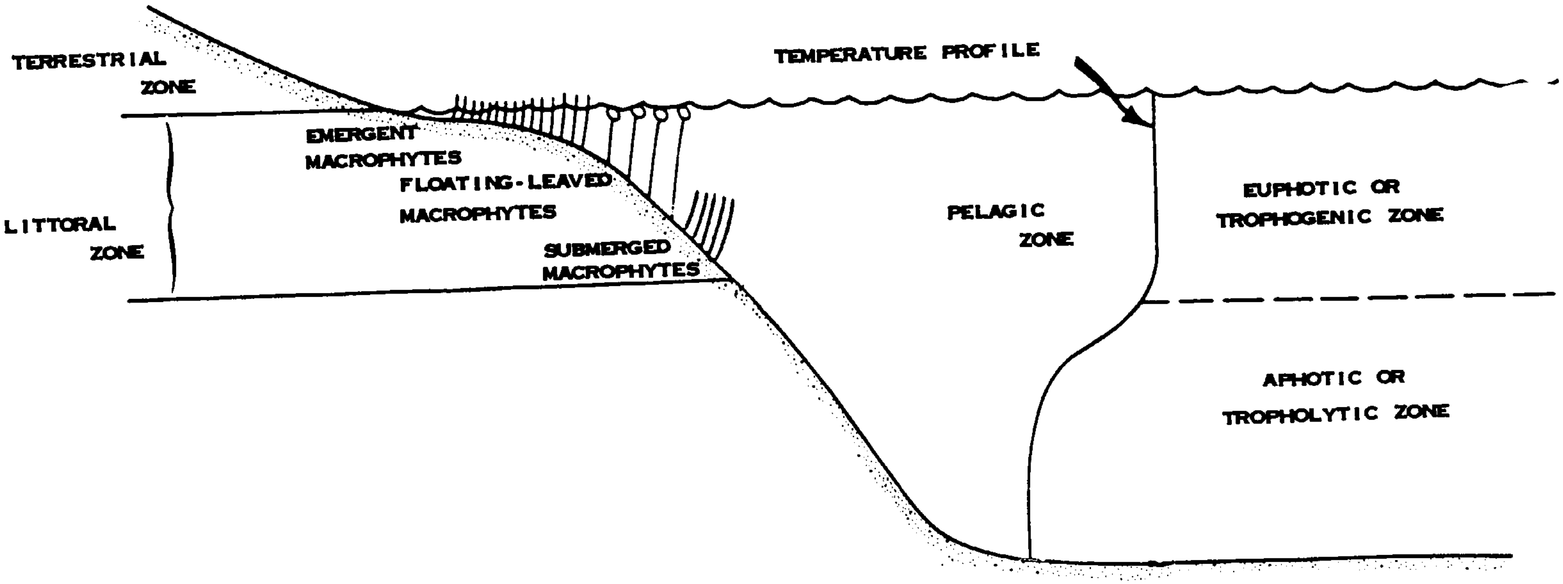


Figure 2-16. Lateral distribution of macrophytes in littoral zone (adapted from Ref. 110)

h. Secondary and Tertiary Productivity. Secondary and tertiary productivity refer to consumption in an ecological food chain (Figure 2-17). Plankton grazers such as zooplankton, benthos, and fish are considered primary consumers, or the first level above the plant producers. Since primary productivity represents the first level or base of productivity, primary consumers represent the second level of productivity, or secondary production (Figure 2-17). Zooplankton, benthic, and fish species that consume the grazers represent tertiary production and secondary consumers (Figure 2-17). Secondary and tertiary production may not directly influence water quality but can have a significant indirect role in reservoir water quality. Phytoplankton, macrophyte, and periphyton consumers or grazers can reduce the abundance of these species and alter succession patterns. The white amur or Asian carp has been used effectively to control macrophytes through consumption. Some phytoplankton species are consumed and assimilated more readily and are preferentially selected by consumers. Single-celled diatom and green algae species are readily consumed by zooplankton while filamentous blue-green algae are avoided by zooplankters. Larger zooplankton can consume larger plankton species, but these larger zooplankton species are also selected by planktivorous fish. Altering the fish population can result in a change in the

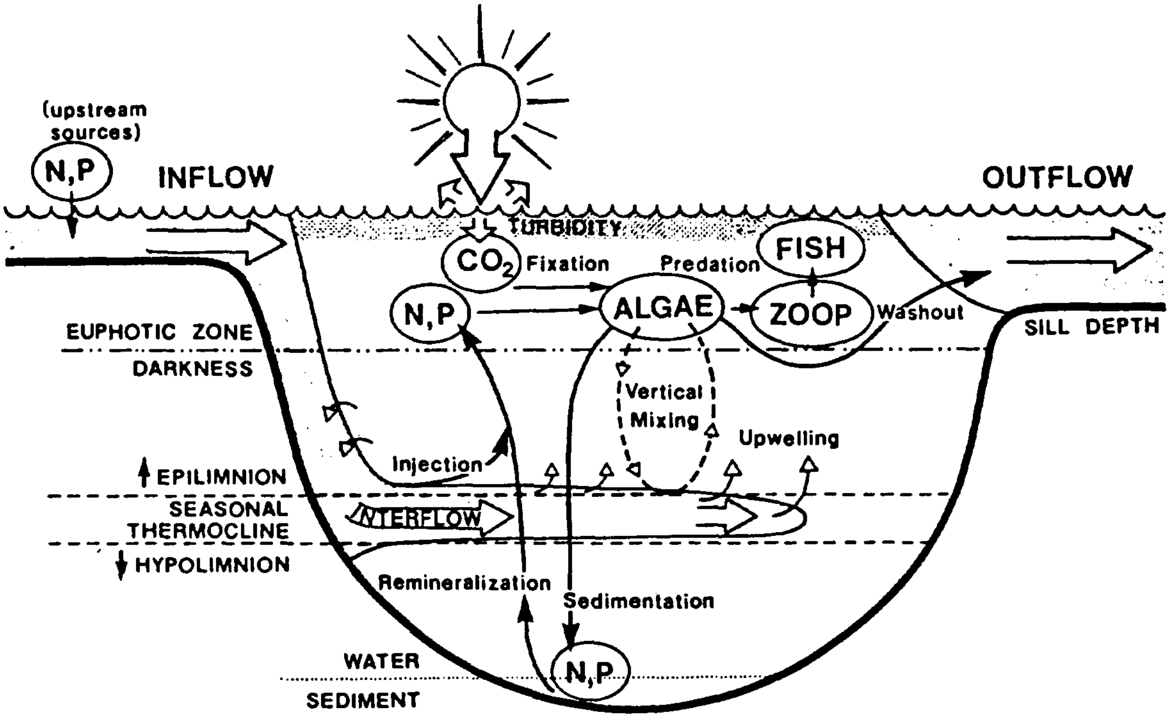


Figure 2-17. Generalized reservoir ecosystem indicating physical, chemical, and biological interactions including higher trophic levels (after Ref. 56)

zooplankton population that can affect the phytoplankton population. This change may be desirable or undesirable depending on reservoir uses. It can be seen from the example of altering fish population that ecological systems are dynamic and highly interactive.

i. Organic Carbon and Detritus. Total organic carbon (TOC) is composed of dissolved organic carbon (DOC) and particulate organic carbon (POC). Detritus represents that portion of POC that is nonliving. Nearly all the TOC of natural waters consists of DOC and detritus, or dead POC. TOC is important in reservoirs for three reasons: decomposition, consumption, and impact on fish.

(1) Decomposition. DOC and POC are decomposed by microbial organisms. This decomposition exerts an oxygen demand that can remove DO from the water column. During stratification, the metalimnion and hypolimnion become relatively isolated from sources of DO, and oxygen depletion can occur through organic decomposition. There are two major sources of this organic matter: allochthonous (i.e., produced outside the reservoir and transported in) and authochthonous (i.e., produced within the reservoir). Allochthonous organic carbon in small streams may be relatively refractory since it consists of decaying terrestrial vegetation that has washed or fallen into the stream. Larger rivers, however, may contribute substantial quantities of riverine algae or periphyton that decompose rapidly and can exert a significant oxygen demand. Autochthonous sources include phytoplankton settling from the mixed layers and macrophyte fragments and periphyton transported from the littoral zone. These sources are also rapidly decomposed.

(2) Consumption. POC and DOC absorbed onto sediment particles may serve as a major food source for aquatic organisms. One study found that 75 percent of all phytoplankton production entered the detritus food web while only 25 percent of the production was grazed by primary consumers. While autochthonous production is important in reservoirs, in some reservoirs as much as three times the authochthonous production may be contributed by allochthonous material.

(3) Fish. Current Corps water quality programs commonly do not involve assessment of fish or fisheries. However, fish are sometimes excellent indicators of water quality conditions. For example, fish can be used as an indicator for identifying gas supersaturation, rapid hydrostatic pressure change caused by some hydraulic structure, pollutants, and anaerobic or anoxic conditions. It is important to remember that the identification and, ultimately, the resolution of water quality problems can involve many disciplines and may necessitate the use of any available tool or knowledge, whether chemical, physical, or biological.

Section IV. Releases and Tailwaters

2-10. Releases.

a. Releases are considered discharges of water from a reservoir that have been impounded by a dam. These discharges are normally controlled by prescribed regulation practices and pass through structural portions of the dam; however, during major flood events the discharges over the spillway can be uncontrolled. Reservoir releases of major concern in Corps water quality studies and programs are the controlled discharges that pass through some portion of the dam, such as a regulating outlet or powerhouse.

b. Reservoir releases are dependent on structural and operational constraints. Discussion will be classified according to these two constraints, as defined below.

(1) Structural. The water released from the surface of the reservoir through a release structure (either a gate or a weir/spillway) is termed epilimnetic release. Multilevel release structures have the capability to release from a combination of levels in the reservoir (i.e., hypolimnion, metalimnion, or epilimnion) or any one level. Typical bottom withdrawal (hypolimnion) structures release water from the bottom of the pool. Surge type reservoirs may have a broad-crested weir with no gates; hence, water comes from the surface of the reservoir and is "skimmed" from the pool.

(2) Operational. Structures with operational capabilities can vary not only the quantity of flow but the timing of flows. Hydroelectric power operation may require high flows for short periods as with a "peaking" operation, while "run of the river" operation may create a much more constant base flow. Flood control releases are dictated by available storage in the reservoirs. If storage capacity is minimal or nonexistent, releases will be high. Navigation projects typically provide releases similar to the preproject riverine environment but are buffered during low-water flow conditions by available storage in each pool. Recreation, water supply, and fish and wildlife releases will be dependent upon project needs and are highly variable.

2-11. Tailwaters.

a. Tailwater is an engineering term that generally refers to the area immediately downstream from a dam that has been changed from its natural state to receive the water released through the dam. This term, describing a physically distinct area, has been conceptually modified in environmental studies to include the downstream portion of the stream channel that exhibits physicochemical and biological characteristics distinct from the natural stream characteristics.

b. The river continuum concept describes changes that occur in organic matter decomposition or production with increasing stream order. Reservoirs can disrupt this continuum. In addition to an altered flow regime, impoundments also alter the thermal regime and concentrations of dissolved gases, nutrients, sediments, and organic carbon. The entire biosphere of the stream is influenced and can be altered by an impoundment. These alterations may represent physical or chemical changes such as decreased temperatures and DO concentrations or biological changes such as modifying species composition in the downstream periphyton or benthic macroinvertebrate community (Figure 2-18).

c. Both the type of release and the morphology of the tailwater may influence the downstream biota and the hydraulics. Releases can be made into a deep or shallow tailwater. Turbulent water will lose excess gas more quickly than quiescent water, either impounded or smoothly flowing. Releases into an impounded tailwater, either a reregulation pool or reservoir headwaters immediately downstream, can have different effects on water quality than a similar release into a stream. If gas supersaturation occurs, for instance, shallow areas downstream of a stilling basin may have fish swimming high in the water column where the effects of supersaturation are the most severe. The subsequent paragraphs discuss some of the principles common to the physics, chemistry, and biology of releases and tailwaters. However, the reader should remember that each tailwater can have peculiarities or unique properties that can result in unique water quality conditions/problems and make the solution to these problems difficult.

2-12. Characteristics and Processes.

a. General. Both the spatial and temporal aspects of the water released from a reservoir affect the quality of the discharges and their subsequent impact upon the quality of the tailwaters. Release quality from a reservoir's spillway can differ considerably from releases simultaneously occurring at the flood control outlet fed by bottom withdrawal gates; steady-state low-flow release quality from a multilevel outlet facility can differ greatly from peak-power generation discharges made through the project's hydroelectric turbines. Further, the quantity and quality of releases from a reservoir affect the quality of water within the reservoir itself. Thus, the interrelationships among the reservoir, its releases, and its tailwater necessitate incorporating the tailwater into a reservoir water quality assessment. (Additional information concerning the effects of reservoir releases on tailwater systems can be found in Refs. 17, 25-27, and 109.)

b. Physical.

(1) Hydrologic regime. Reservoir design and operation typically modify the natural stream discharge. Flood control projects reduce the magnitude of the flood peak but extend elevated discharges over a longer period; navigation projects maintain a minimum downstream channel depth and flow; and peaking hydropower projects release large flows during generation and minimum flows during nongeneration periods, which can vary on a daily basis. These altered flow regimes can result in altered downstream hydraulic characteristics such as the energy gradeline, hydraulic radius, stream sediment-carrying capacity

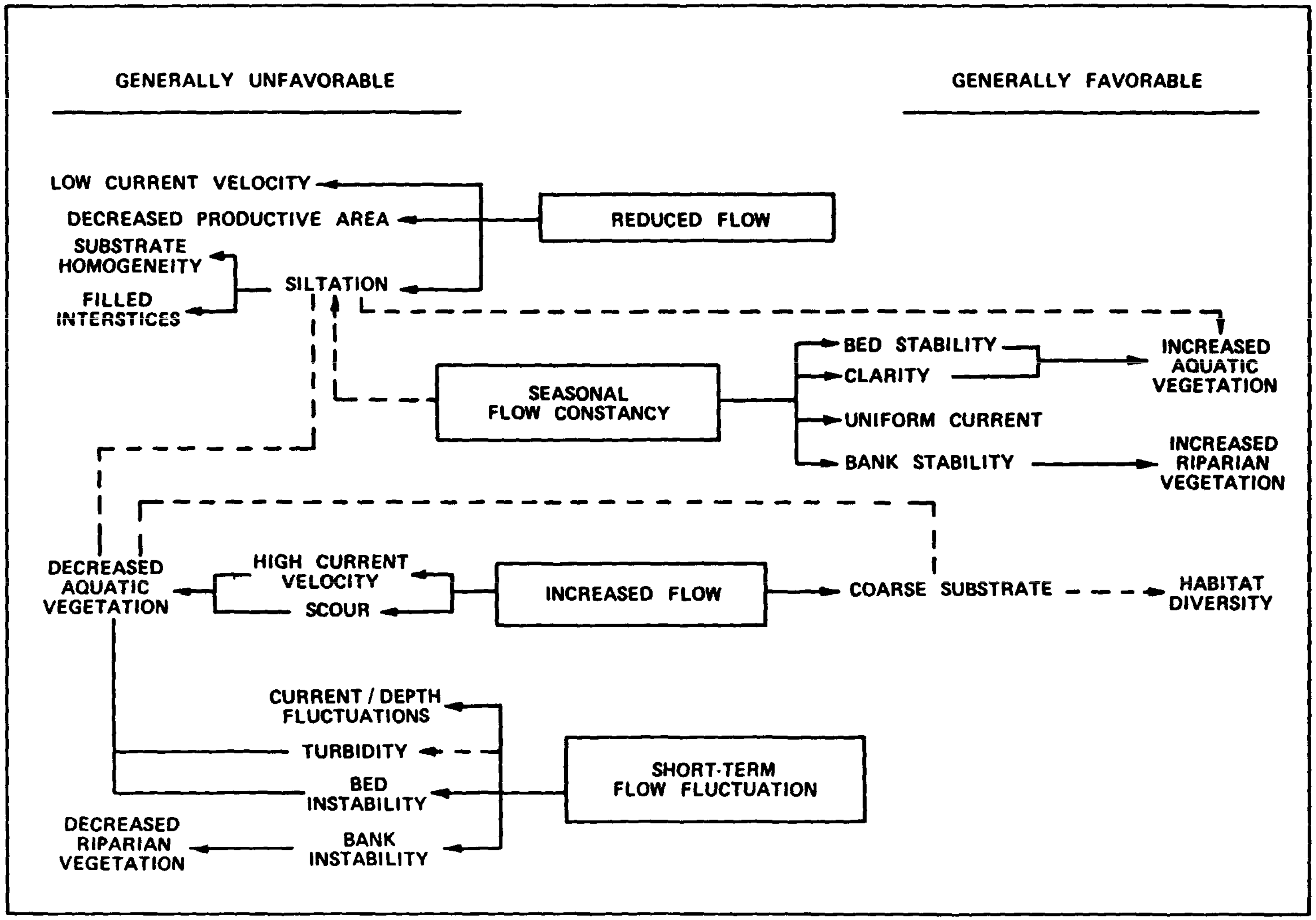


Figure 2-18. Potential effects and interactions of modified flow regime on downstream biota (after Ref. 108)

resulting in bed scour or deposition, and pool-riffle relationships. These altered flow regimes impact related factors such as chemical dilution, biological acclimation to reservoir-altered environments, and impacts of basic mode changes in project operation. Streambank erosion or slumping may occur because of the altered flow regime. Potential impacts of an altered flow regime are discussed in most texts on open channel flow or sediment transport.

(2) Thermal regime. Because of the specific heat of water and the large reservoir water mass, tailwater temperatures warm more slowly in the spring and cool more slowly in the fall than natural stream temperatures, even if the reservoir does not thermally stratify. In thermally stratified reservoirs, the hydraulic outlet location and operation determine the downstream thermal regime. Bottom withdrawal can result in cold downstream temperatures throughout the year or until the supply of cold hypolimnetic water is depleted. Selective withdrawal can be used to meet a downstream temperature objective if an adequate coldwater supply exists in the reservoir. However, due to bottom withdrawal of hypolimnetic waters, fall turnover can occur earlier because of the reduced density gradient between the epilimnion and hypolimnion. Hydroelectric power releases may continually subject the downstream system to pulses of cold water throughout the stratified period.

(3) Turbidity. Tailwaters are usually clearer (less turbid) than the reservoir inflow, particularly below deep reservoirs. Turbidity below reservoirs is affected by sedimentation within the reservoir, density currents, discharge depth from the dam, and the inflow from surface runoff and tributary additions. Turbidity was reduced up to 60-fold in the tailwater below Yellowtail Dam, Montana, by the settling of suspended matter within the reservoir. However, density currents carrying fine suspended matter may sometimes flow beneath or through the main body of water in stratified reservoirs and be discharged directly into the tailwaters with little alteration within the reservoir. In these instances, mineral concentrations and turbidity may increase significantly in the tailwater. Turbid conditions may also result from the flushing of loose materials into tailwaters, from unstable riverbeds and streambanks during periods of high discharge, and from tributary inflow.

(4) Zone of influence. Air temperature, discharge volume, ground-water and tributary additions, shade, and substrate type all play a role in modifying the tailwater temperature as the water moves downstream. At some point downstream, where the influence of the reservoir is not significant, the interaction of these factors results in the return of the stream to preimpoundment conditions.

c. Chemical.

(1) Gas exchange. The gas conditions of greatest concern are low DO concentrations and gas supersaturation. Reservoir releases may also contain ammonia or hydrogen sulfide concentrations that do not completely dissipate to the atmosphere after leaving the conduit or draft tube and entering the

tailwater. These constituents can be harmful to various macroinvertebrates or fish species.

(2) Dissolved oxygen. Reservoir release DO concentrations are a function of hydraulic outlet design and reservoir DO concentrations at the depth of withdrawal. The DO concentrations in releases from nonhydroelectric power projects range from 80 to 90 percent of saturation even if the releases come from an anoxic hypolimnion. Reaeration of the flow occurs primarily through turbulent mixing as flow passes through the gated outlet. Constituents such as ammonia and low-molecular weight organics may cause an oxygen sag farther downstream as they are oxidized, however, even if releases are 100-percent saturated with DO. Reduced iron and manganese are generally oxidized in the conduit but can be transported downstream in a particulate form. Selective withdrawal also can be used to increase release DO concentrations and to meet a downstream temperature objective. Hypolimnetic withdrawal from an anoxic hypolimnion for hydropower generation generally results in low release DO concentrations since hydraulic design considerations reduce turbulence to minimize back pressure on the turbines and increase generation efficiency.

(3) Nitrogen supersaturation. Gas (primarily nitrogen) supersaturation generally represents the gaseous condition of greatest concern, with the exception of DO, in reservoir releases. Gas supersaturation may occur under two circumstances, spillway entrainment and hypolimnetic aeration.

(a) Spillway entrainment. A common form of gas supersaturation occurs when flow is discharged over a spillway and enters a deep-plunge basin. As water flows down the spillway, it is saturated with atmospheric gases. If this saturated flow plunges into a deep stilling or plunge basin, hydrostatic pressure can force the gas into solution. Fish or other organisms in the stilling basin can absorb this dissolved gas. Then, when they enter an area with lower hydrostatic pressure, the gas comes out of solution and forms gas bubbles that can cause embolisms. This condition, called gas bubble disease, can be fatal to fish and other organisms.

(b) Hypolimnetic aeration. Hypolimnetic aeration with compressed air can result in nitrogen (N_2) supersaturation of the reservoir releases if there is sufficient hydrostatic pressure in the reservoir. Hydrostatic pressure forces some N_2 gas into solution. Since hypolimnetic aeration usually is associated with hydropower projects (Figure 2-19), N_2 gas is not dissipated by turbulence after discharge from the draft tube. Fish that enter this N_2-supersaturated water can transfer the dissolved N_2 across their gill membranes into their bloodstream. When the fish leave this area and enter a lower pressure area, gas bubble disease can result.

(4) Phosphorus and ammonia-nitrogen. Nutrient concentrations in reservoir releases are directly related to the reservoir water quality. Reservoir trap efficiencies are high for particulate matter. As a result, removal of

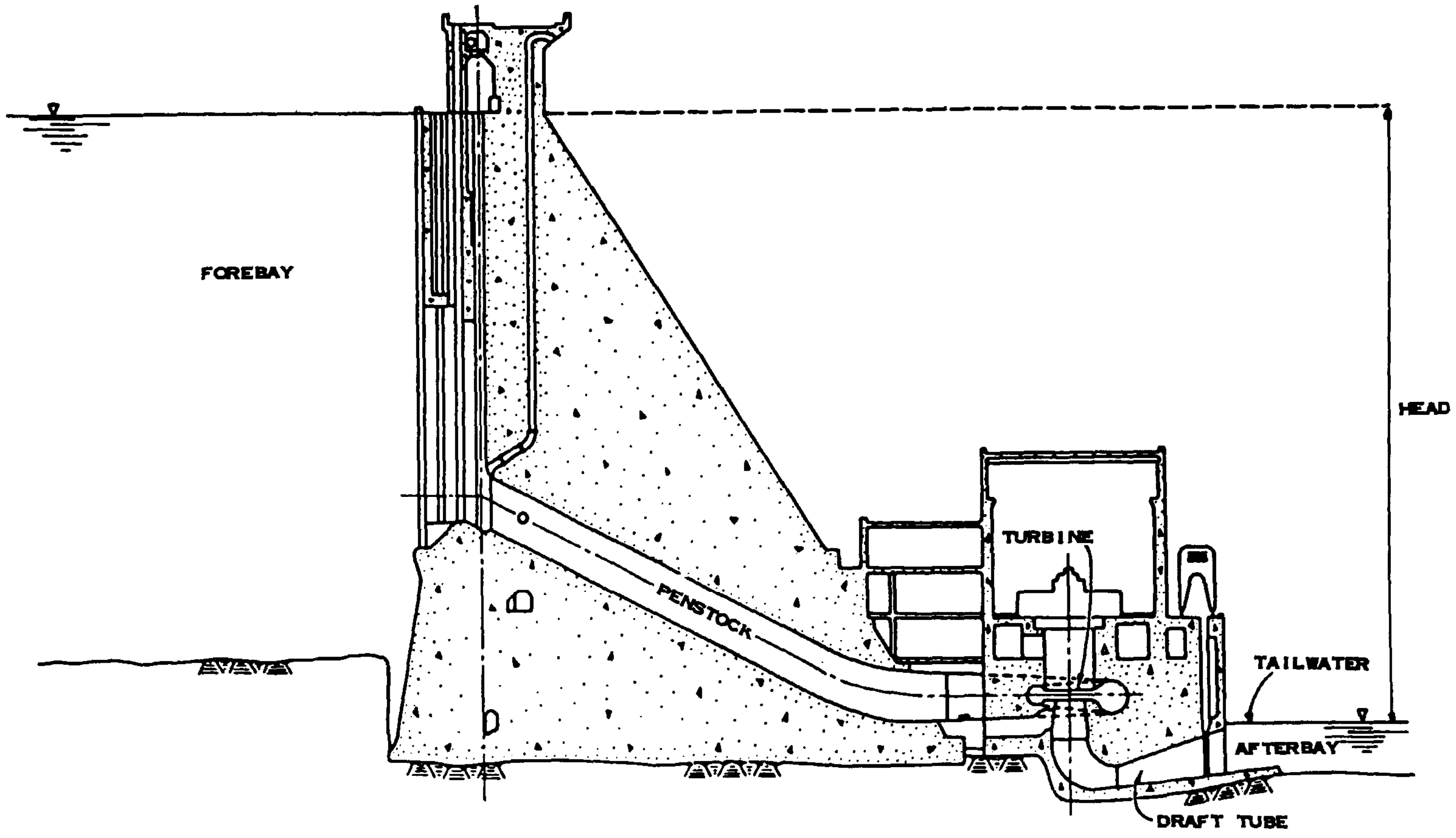


Figure 2-19. Schematic of a hydropower facility

particulate nutrient species along with plankton nutrient uptake and use can cause low nutrient concentrations in reservoir releases. Release nutrient concentrations from reservoirs with surface withdrawal generally increase following fall turnover and the mixing of hypolimnetic nutrients throughout the water column. Releases from an anoxic hypolimnion, however, may easily result in dissolved phosphorus and ammonia-N concentrations that are an order of magnitude greater than reservoir epilimnetic concentrations. These releases may subject the downstream system to pulses of nutrients during the peak of the growing season.

(5) Particulate organic carbon (POC). POC represents an important component of the food supply for macroinvertebrates in natural stream ecosystems.

(a) Epilimnetic release. Reservoirs with surface withdrawal can increase release POC concentrations by discharging epilimnetic plankton. The POC concentrations have been found to be 85 percent more abundant in surface releases than in the inflowing tributary. The POC concentrations in surface releases reflect plankton dynamics in the reservoir. (Item bb provides a more detailed discussion.)

(b) Hypolimnetic release. Reservoirs with bottom withdrawal have substantially lower release POC concentrations that the unregulated upstream tributaries. The POC quality also may be altered since the median particle size usually is smaller than upstream tributaries and the POC may be quite refractory.

(c) Hydroelectric power release. The highest POC concentrations can be associated with the initial downstream surge of water at the start of the generation period (Figure 2-20). In the Lake Hartwell tailwater, POC concentrations were 200 to 300 times greater than during nongeneration periods. The POC concentrations generally decrease rapidly following the initial surge, but the total transport (i.e., flow concentration) generally is highest during the generation period. With bottom withdrawal, the source of POC may be scour of tailwater periphyton and macrophytes. These POC particle sizes are generally small.

d. Biological. The aquatic habitat downstream from the reservoir is controlled to a large extent by the reservoir and the releases from the dam. Understanding the biological processes associated with water quality in the reservoir tailwater, therefore, requires an understanding of the reservoir and its associated processes. It should be noted, however, that some processes important within the reservoir system either do not occur or are inconsequential in the tailwater.

(1) Microbiological. Microorganisms are limited primarily to sedimentary and periphytic activity but, due to the relatively high velocities associated with discharges, are most often a small portion of the biome. Consequently, biological activity by these organisms should have very little impact on water quality.

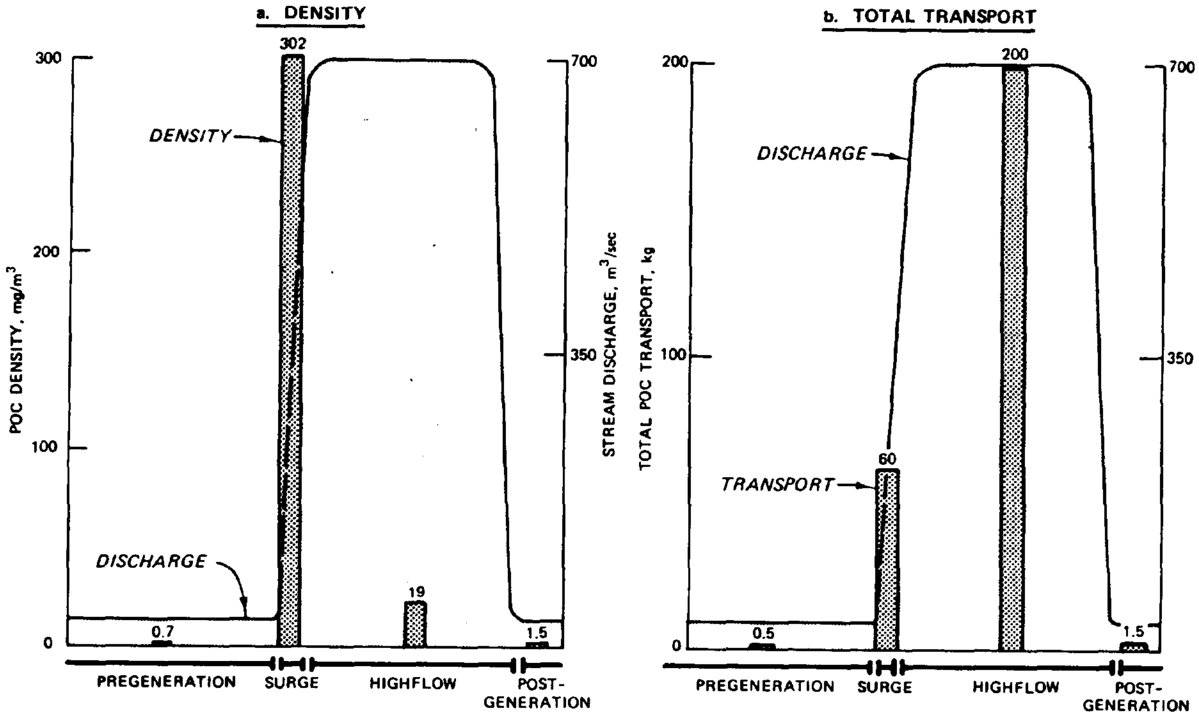


Figure 2-20. POC concentrations and transport during hydropower generation cycle (after Ref. 17)

(2) Photosynthesis and primary productivity. Tailwaters immediately below dams usually are autotrophic because of the control exerted on the watershed by the dam. If the discharge is nutrient rich with a relatively low level of turbidity, production of algae may be stimulated. Further downstream, as the river becomes more heterotrophic, photosynthesis and primary productivity will be reduced to play only a limited role.

(3) Temporal variability. Phytoplankton in tailwaters are controlled both by nutrient levels in the release water and hydraulic conditions of the tailwater, with density of organisms (both zooplankton and phytoplankton) decreasing with distance downstream. With most planktonic organisms, abundance is related to available habitat, which in the case of these organisms relates to quiet, slow-moving water. Temporal variability is thus reduced to temperature, light, available nutrients, and predators. The upstream reservoir may exhibit succession in algal species, which will be exhibited to a certain extent in the tailwater but may be phased (i.e., peaks in green algae in the discharge following the peaks in the reservoir).

(4) Macrophytes. Macrophytes in tailwater are limited to littoral areas and relatively stable pools. Since tailwaters are dynamic with respect to depth and discharge, they do not provide suitable habitat for most higher

plants; however, areas that are subject to frequent inundation may support bryophytes. The sediments in most tailwater are composed of grains coarser than those in the reservoir and usually will not support rooted aquatic plants. As with other environmental constituents, the reader should be aware that the reservoir condition, spillway design, operational plan, and meteorological conditions all interact at specific tailwater sites to control the growth or lack of aquatic plants.

(5) Periphyton. Periphyton algae grow attached to a substrate such as rocks, macrophytes, pilings, or timber. Tailwater periphyton may serve two purposes: removing nutrients from the flowing water, although nutrients may be returned to the aquatic system upon the death of the organisms; and serving as a food reserve for zooplankton, benthos, or various fish species.

(6) Secondary and tertiary productivity.

(a) Project operations affect downstream biota in numerous ways. Large flow variations may adversely affect downstream productivity by impacting spawning periods and disrupting benthic populations. In addition, cooler releases slow chemical and biological reactions, thus reducing productivity in the affected reach.

(b) Epilimnetic reservoir releases usually are less disruptive to tailwater biota than hypolimnetic releases. The macroinvertebrate and fish species are typical of the natural stream system, but community structure depends on reservoir operation such as duration and quantity of low-flow releases, flood releases, etc. Fish species found in the reservoir usually are also found in the tailwater, as these species pass over the spillway through the outlets or were a part of the stream system before impoundment. Although lower nutrient concentrations in releases can result in lower primary production in the tailwater, the export of reservoir plankton can compensate for this reduction by supplementing the food supply for the macroinvertebrate and fish species.

(c) Coldwater release temperatures may be below temperature tolerance levels for both macroinvertebrate and fish species in natural warmwater systems. The altered release temperatures may disrupt normal temperature queues for spawning, hatching, emergence, and development of many biotic species. Coldwater releases are not as disruptive for naturally coldwater streams, as long as sufficient hypolimnetic volume is available to maintain coldwater releases and releases are not made from an anoxic hypolimnion. POC particle sizes generally are smaller than upstream, giving a competitive advantage to filter-feeding macroinvertebrates. Benthic shredders, normally feeding on and living in accumulations of large particulate matter such as debris piles and leaf packs, may have limited food supply and habitat.

(d) Large diurnal flow fluctuations can have a deleterious effect on many macroinvertebrate and fish species. While the diversity of species generally decreases, those species that are able to tolerate the large flow variations can become abundant. Macroinvertebrate densities also may increase markedly during the initial downstream water surge at the start of the generation period. Macroinvertebrate transport is greatest during generation, but many of these invertebrates may originate in the reservoir and be transported into the tailwater, supplementing the food supply for the tailwater fisheries. Nongeneration periods may strand some fish and macroinvertebrate species and result in their desiccation.

(7) Decomposition and consumption. See para 2-12c(5).

(8) Fish. See para 2-9i(3).

CHAPTER 3

WATER QUALITY ASSESSMENT

Section I. Designing the Assessment Plan

3-1. Establishing Objectives.

a. General. This chapter provides guidance on setting water quality assessment objectives for programs and/or studies, and on developing designs for reservoir water quality assessment studies. Six typical reservoir study types are considered, and an example of each type is presented for illustration. Before initiating any water quality assessment, the objectives of the program or study need to be specified in a clear and concise manner. This chapter details a process for identifying study objectives and addressing them in a quantitative manner. Once study objectives have been clearly defined, appropriate methods to address them can be selected and a plan of study developed.

b. Interdisciplinary Approach. Assessing reservoir water quality is multifaceted and requires expertise from many disciplines. Since this expertise can rarely be found in any single individual or discipline, an interdisciplinary approach may be required to analyze and address water quality objectives. An interdisciplinary approach implies multiple disciplines (e.g., engineering, physics, chemistry, biology, economics, etc.) cooperating and interacting to address water quality objectives, not simply the assemblage of multiple disciplines working independently on a problem. Corps of Engineers District and Division offices are uniquely suited to using the interdisciplinary approach on water quality issues because the required multidisciplinary expertise exists in many Corps field offices. The three major elements in most field offices--Planning, Engineering, and Construction/Operations--all have responsibility for various aspects of reservoir water quality. Objectives identified and addressed during the initial planning phases can minimize problems during later design phases and, subsequently, during reservoir operation and management.

c. Steps in Establishing Objectives. Establishing the objectives of a water quality program or study is a crucial step in developing a technically sound water quality assessment. Although setting the objectives for a water quality program or study seems to be an obvious step, this process and its documentation are often overlooked. Establishing objectives involves identifying the water quality issues and the potential causes of problems and differentiating the causes from the symptoms. Once the problem or situation has been identified, a written assessment must be completed in order to make the objectives attainable. The objectives should be simple written statements that describe the action to be taken and the measurable key result within a defined time frame and a specified budget.

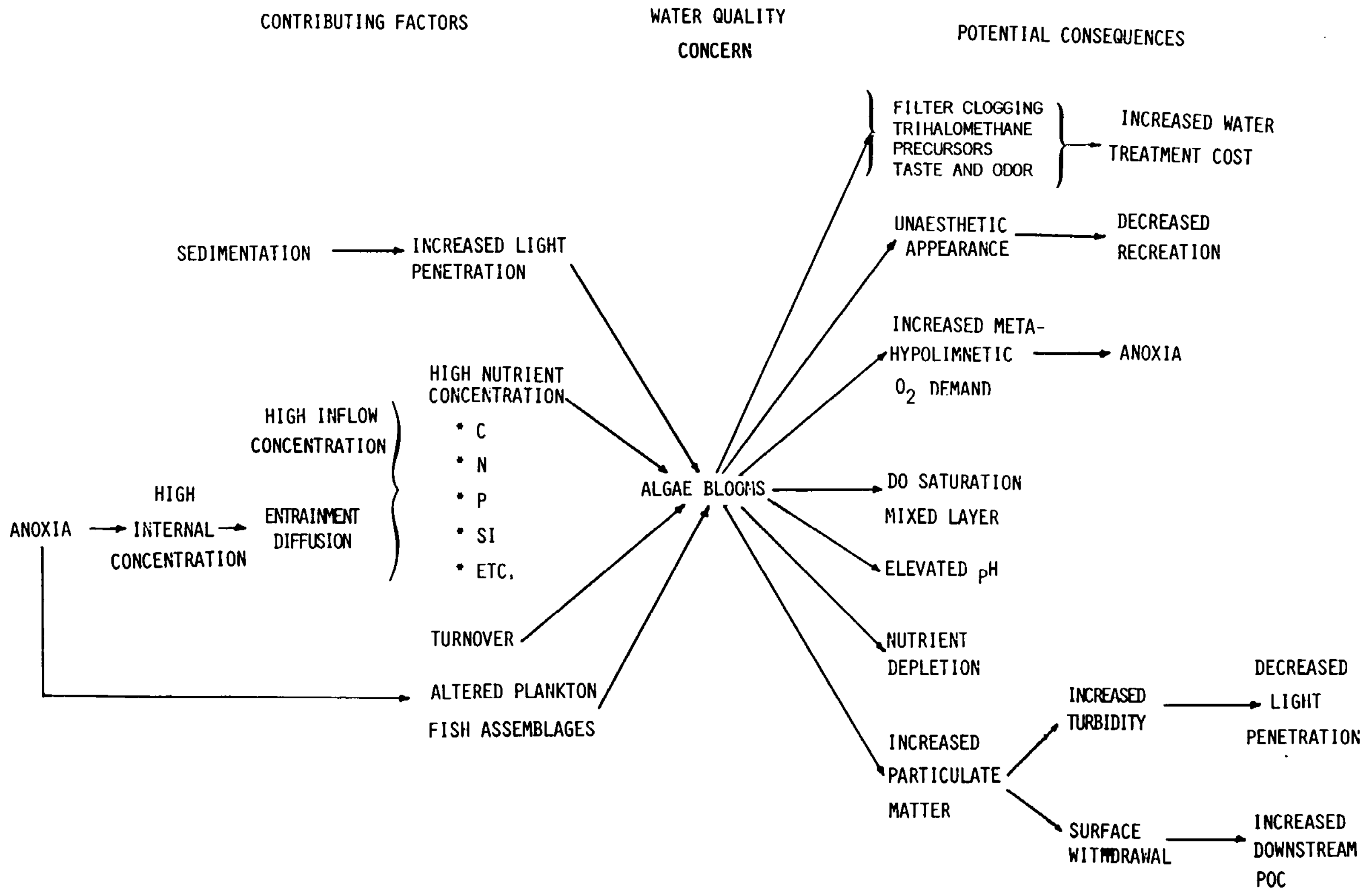


Figure 3-1. Contributing factors and potential consequences of algae blooms

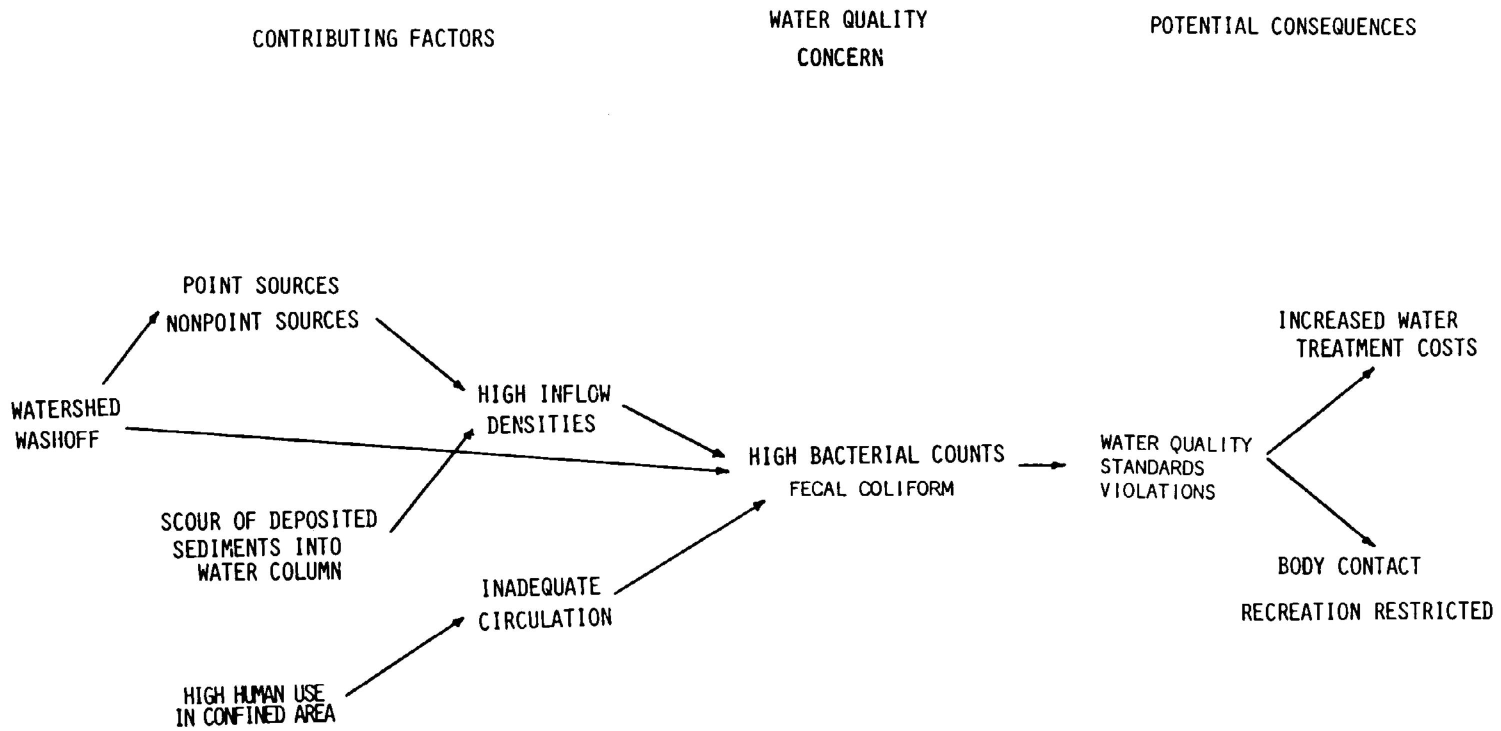


Figure 3-3. Contributing factors and potential consequences of high bacterial counts

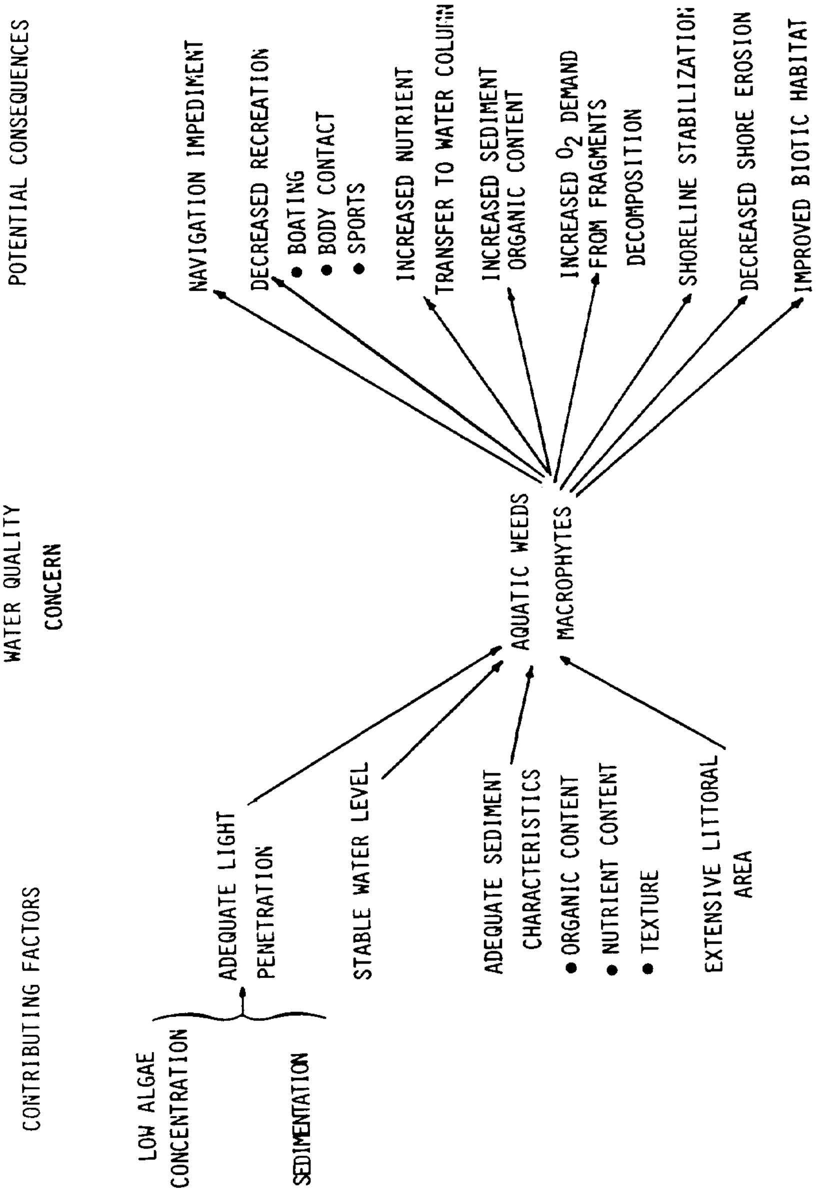


Figure 3-2. Contributing factors and potential consequences of aquatic weed infestations

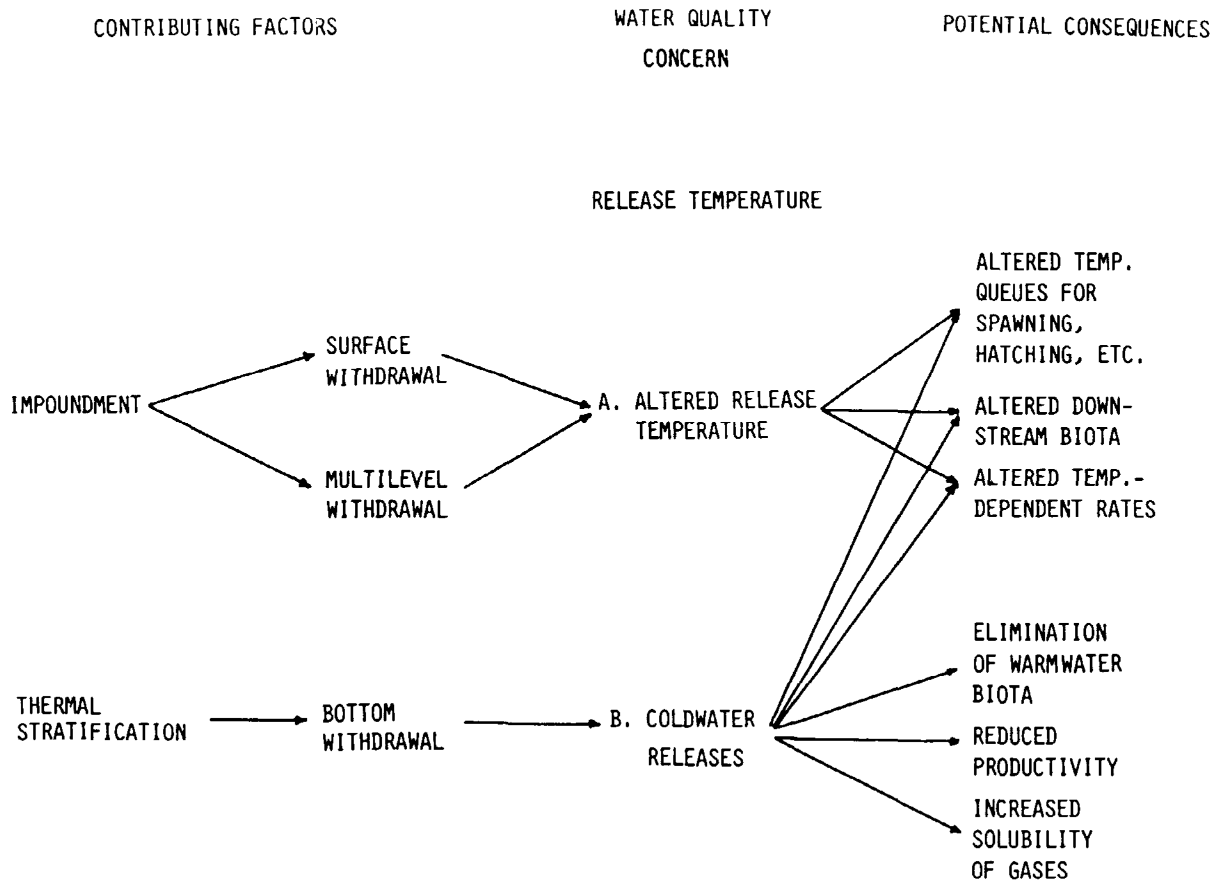


Figure 3-4. Contributing factors and potential consequences of altered release temperatures

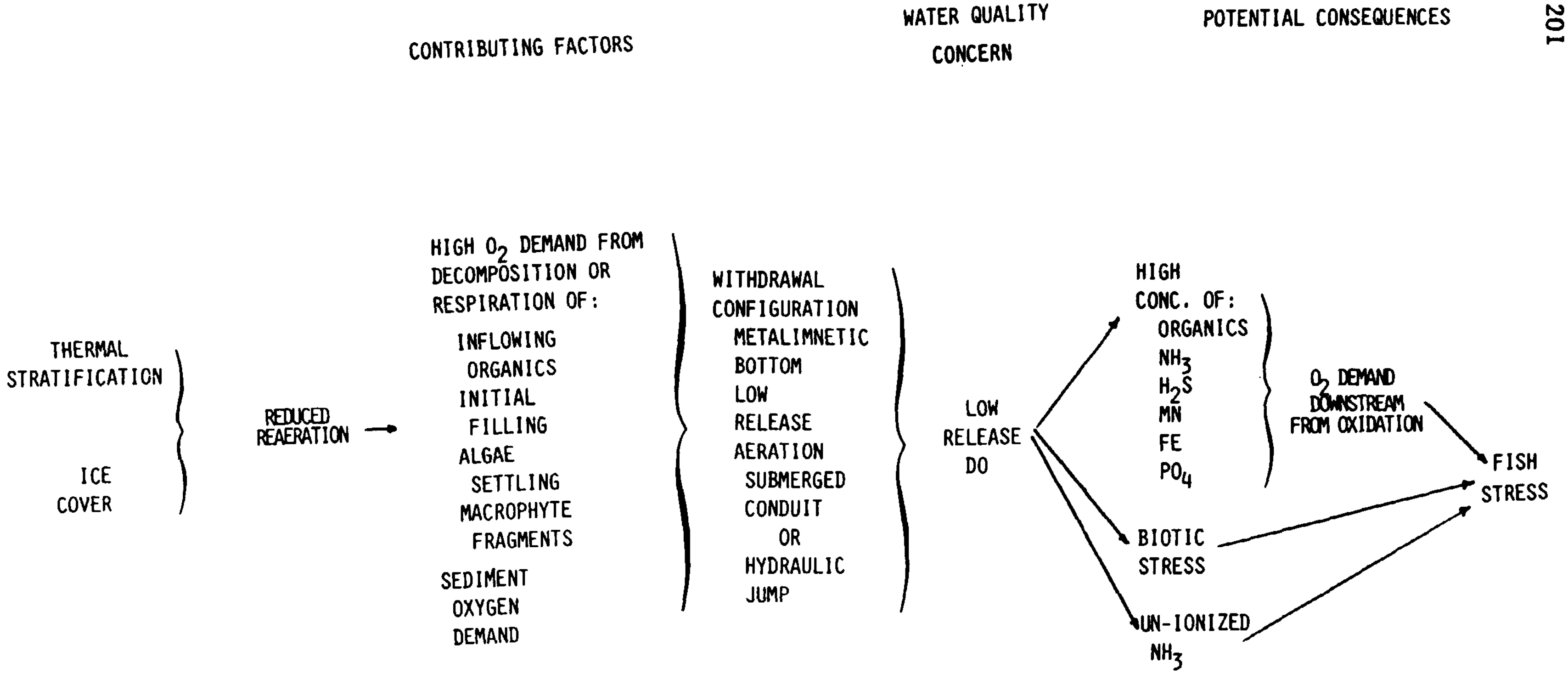


Figure 3-5. Contributing factors and potential consequences of release DO concentrations

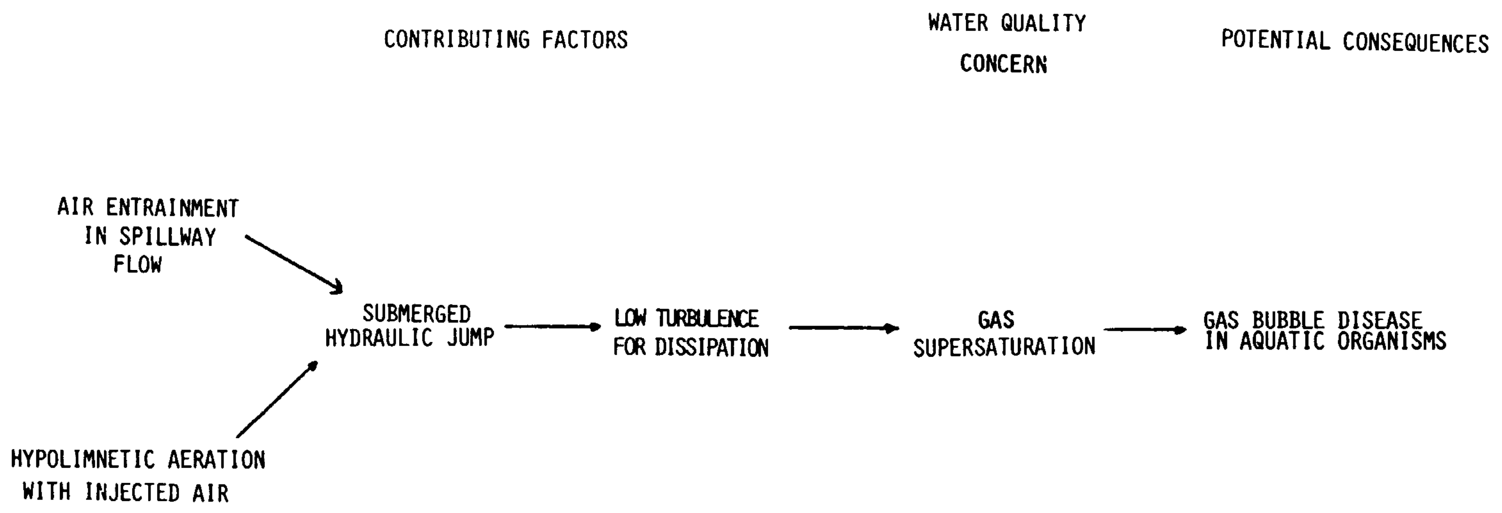


Figure 3-6. Contributing factors and potential consequences of gas supersaturation

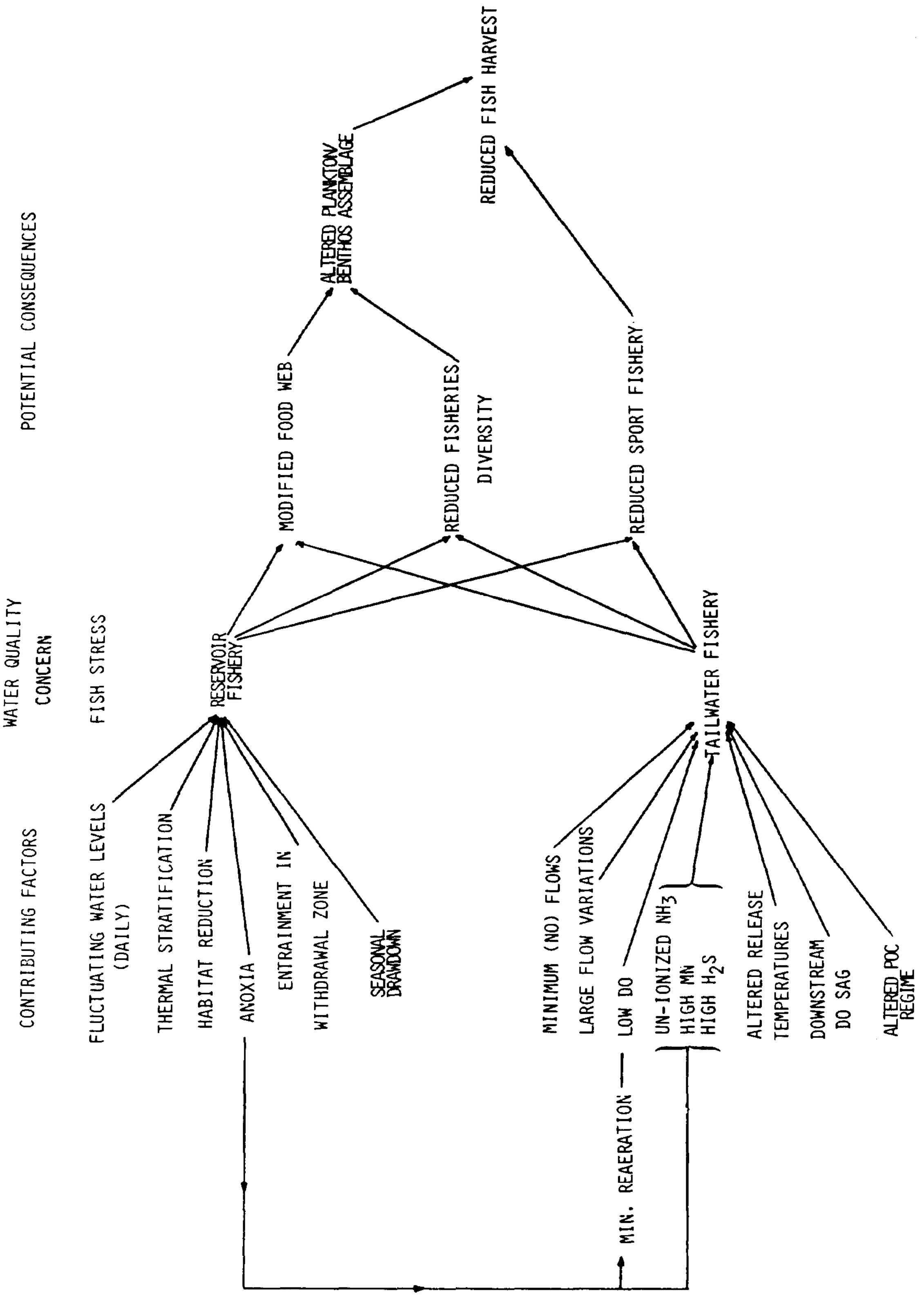


Figure 3-7. Contributing factors and potential consequences of fish stress on both the reservoir and tailwater fishery

TABLE 3-1

Water Quality Concerns and Possible Contributing Factors

POSSIBLE CONTRIBUTING FACTORS / WATER QUALITY CONCERNS	Large Flow Variations	Scour	Erosion	Mudflats	Cold Release Temp.	Un-natural Release Temp.	Low Release DO	High Release Metals (e.g. Fe, Mn)	High Release NH_3, H_2S	N_2 Supersaturation	High Turbidity	High SS	TDS/Salinity	High Nutrient Conc.	High pH	Low pH	Contaminants	Organics	Taste & Odor	THM Precursors	Algae Blooms	Aquatic Weeds	*F. coli* Bacteria	Fish Stress
Bottom Withdrawal					●		●	●	●								●	●	●	●				●
Plunging Spillway Flow		●								●														●
Hydropower Operation	●	●			●		●	●	●	●							●	●	●	●				●
Fluctuating Water Level			●	●							●	●												●
Stable Water Level																					●	●		
Large Fetch/Waves		●	●								●	●												
Limited Mixing														●							●	●	●	
Extensive Littoral Areas																					●	●		
Watershed Land Use e.g. Agric/Urban							●				●	●	●	●		●	●	●	●	●	●		●	●
High Sediment Inflow							●				●	●		●			●	●				●		●
High Nutrient Inflow							●							●							●			
High TOC Inflow							●										●	●	●	●				
Point Sources											●	●		●	●	●	●	●	●	●	●		●	●
Stratification					●	●	●																	
Ice Cover							●																	
High Evaporation													●	●										
Sed. Oxygen Demand							●																	●
Organic Decomposition							●	●	●					●			●	●	●	●	●			
Anoxia							●	●	●					●			●	●	●	●				●
Reduced Chem. Species								●	●								●	●	●	●				●
Internal Nutrient Load									●					●							●			
High Algal Prod.							●				●				●			●	●	●	●			
High Macrophyte Prod.							●							●	●			●						

(1) Identify water quality concerns. Diagrams similar to Figures 3-1 through 3-7 or a table similar to Table 3-1 are valuable tools in identifying the factors that could potentially contribute to water quality problems. Each discipline and functional group of an interdisciplinary team has a different perspective on water quality concerns, which is important in identifying potential problems.

(2) Identify potential causes. Some water quality concerns occur in nearly all Corps reservoirs and are a result of similar internal processes, external forces, and water control procedures. Seven of these water quality concerns, and their potential causes and consequences, are shown in Figures 3-1 through 3-7. Three of these relate to reservoir water quality; three issues relate to release water quality; and the final concern relates to both the reservoir and tailwater. Similar diagrams can be developed for other specific water quality issues or concerns. Possible causes of other water quality problems are listed in Table 3-1 and may aid in the identification of potential factors affecting reservoir water quality.

(3) Differentiate causes and symptoms. During the identification of potential causes, it is critical that causes be distinguished from symptoms. However, determining the potential causes of a water quality problem can be difficult. Cosmetic, short-lived solutions result from applying management techniques that address water quality symptoms and not causes. Management approaches that address causes typically are more cost effective than approaches that address symptoms. The interdisciplinary group is critical in this phase.

d. Determining Priorities. After needs have been identified and objectives established, a determination must be made as to what work can be done based on the priority of needs and the available resources. When many objectives are involved, management by objective tools, such as decision matrices, is helpful. The developed priorities should be considered tentative and subject to change based on changing needs and resources. Priorities based on program objectives generally differ from those of studies.

(1) Program objectives. Setting priorities for program objectives, such as those that are part of an operational monitoring program, consists of determining those objectives that are basic to the mission of the organization ("must do"), those that are necessary for improving the effectiveness of the organization ("ought to do"), and those that are highly desirable for improving the effectiveness of the organization ("nice to do"). Generally, the "nice to do" objectives are postponed during unanticipated program changes such as budget or personnel reductions. "Ought to do" objectives can be delayed if conditions warrant. Conversely, "nice to do" objectives can be accelerated if personnel or budget conditions improve.

(2) Study objectives. After the water quality concerns have been identified, these should be ordered by dominance, magnitude, controllability, and impact, and a priority should be assigned for formulating management

approaches. For a particular concern, the order of importance and its priority may not be identical. Some issues may be easily addressed with limited funds. These issues may receive a higher priority for initial study than factors requiring longer term planning and coordination with other agencies. A dual priority system may be considered for short-term remedies and long-term solutions.

e. Reevaluation. A reanalysis of water quality concerns and programs may determine that some concerns are more important than originally anticipated. A reevaluation should be conducted, and reassessment of priorities may be required. The evaluation should be an iterative and ongoing process.

f. Modification. Changes in the priority ranking of objectives, or changes in the objectives themselves, should be completed by preparing a revised priority listing of objectives.

3-2. Design Considerations. Once the objectives have been determined, a design or plan of action for achieving those objectives must be prepared. While each design must be tailored to the specific assessment being conducted, the following considerations provide general guidance on the subject.

a. The general characteristics of the assessment should be outlined. Phasing should also be considered, particularly if certain items can only be addressed in sequence or are based on results from another activity. Responsibilities for the various parts must be identified (e.g., is there in-house capability, or will portions or all aspects of the work be contracted?). Level of detail should be described, with scheduling and available resources outlined.

b. It may be helpful to initially evaluate similar studies; many water quality problems or concerns are unique to reservoirs but are common among Federal projects. Discussions with other field operating activities, the Tennessee Valley Authority, or the Bureau of Reclamation can identify ongoing studies, describe consequences or impacts, or warn of pitfalls to avoid.

c. The plan of action will help determine the overall success of the reservoir water quality assessment. It will ensure that the assessment provides conclusions and recommendations that address the specific objectives defined at the beginning, or as redefined during the study. Although this appears obvious, many assessments diverge and subsequently resolve an entirely different set of objectives or problems than originally defined.

d. The design should ensure that the assessment results and conclusions are clearly presented and discussed. In some instances, conclusive results are lost in poor presentation and confusing discussion. As a result, cost-effective, environmentally and technically sound water quality management techniques might not be implemented. The results and conclusions from an assessment need not be voluminous or finely detailed to specifically answer questions, but the information must be clearly understandable.

e. Conclusions and recommendations from all assessments must indicate the reliability of the result and the dependability of the proposed management techniques. These estimates of dependability are essential for rational decision-making in water quality management. A management technique that is 25 percent more expensive but has a 95-percent probability of being effective may be selected over another less expensive technique with only a 50-percent probability of success.

f. Each reservoir project is unique, and the selection and application of appropriate assessment techniques to address issues may require modifications prior to implementation. It should not be assumed that techniques developed for reservoirs in the Northeast are directly applicable to reservoirs in the Southwest and vice versa. Each assessment technique must be carefully evaluated prior to application.

g. A final consideration in designing an effective water quality assessment plan is the importance of project familiarity. Activities such as visiting the project site and working with existing data allow an individual to make common sense or technical judgments pertinent to the quality of the water, problem areas (either existing or developing), and general operating characteristics. This type knowledge cannot be obtained by simply reviewing data. A lack of project familiarity can jeopardize the position of the responsible Corps element should a problem arise.

3-3. Elements of Assessment.

a. Six general categories of reservoir water quality assessment studies are discussed in Section II. A representative example from each category is used to illustrate the general assessment approach. Discussion for each category includes the expected consequences of the proposed actions and a number of program or study definitions.

b. The program or study definitions include known factors, factors to be determined, and assessment techniques, as outlined below.

(1) Known factors. Certain information that is required to address the program or a specific study is readily available before initiating any study. This information includes knowledge of the project purposes; hydrometeorological records; basin and reservoir geometry; water control procedures; and inflow, inlake, or release water quality. This information must be collated for use in subsequent analyses.

(2) Factors to be determined. The unknown factors are dictated by the program or study definition. These are the water quality characteristics that must be determined in order to evaluate whether a reservoir water quality problem may occur and its probable magnitude, duration, and frequency. This must be an iterative process. It is quite possible to address factors that will not contribute to problem solution. This misdirection generally indicates either the problem is not understood or has not been properly defined.

Coordination and discussion of reservoir water quality concerns with the US Environmental Protection Agency (EPA), State and local agencies, or other interested groups can assist in refining study objectives and determining the important factors to evaluate during the study. Most agencies have a greater interest in and are more receptive to study results and conclusions if they were involved in formulating the pertinent study questions and study plan.

(3) Assessment techniques.

(a) There is no single technique or approach for addressing all water quality-related engineering activities or water quality problems. Therefore, the use of only one technique in reservoir water quality studies is not warranted. Each technique has inherent assumptions and limitations that must be considered during technique selection, application, and interpretation of results.

(b) It is important to use the technique that is best for the program or study, not necessarily the technique most familiar to the user. User familiarity is important in technique selection but not to the exclusion of better methods.

(c) Since every reservoir is a unique system, techniques may require modification prior to use. Knowledge of the project characteristics and the assessment technique is crucial for technique modification and accurate analysis. Incorporation of site-specific characteristics in the methodology is generally the best approach for assessing water quality conditions or impacts of engineering design alternatives.

(d) The extent of analysis and the required detail are determined by the program or study scope, available information, required resolution, and engineering and scientific judgment. Some water quality concerns can be resolved in a day using order of magnitude estimates, while other water quality concerns may require field and laboratory investigations and mathematical and physical model applications that extend for a year or more to develop satisfactory management alternatives.

(e) One generalization is valid over the broad range of analytical techniques. That is, an integrated approach, using multiple techniques, results in a more reliable, cost-effective, and sound engineering analysis of potential water quality problems and the alternative management approaches.

Section II. Water Quality Assessment Program/Study Categories

3-4. Preimpoundment Assessment. A preimpoundment assessment predicts the reservoir water quality conditions that are likely to occur in and below a project if it were constructed and operated under a specific engineering design and water control plan. In general, a preimpoundment assessment evaluates several alternative engineering designs and alternative water control plans.

a. Expected Consequences. The obvious consequence of a proposed reservoir is that a free-flowing stream or river will be impounded. General reservoir water quality characteristics and water quality patterns that can be expected are discussed in Chapter 2. Study of the reservoir water quality at surrounding reservoirs with similar structural designs and water control plans provides valuable insight into the water quality patterns and problems to be encountered at the proposed study site. For most reservoirs, dynamic water quality changes can be expected for the first 6 to 10 years following impoundment, during the transition period.

b. Program/Study Definition. Two related concerns associated with any preimpoundment assessment, regardless of project type, are whether postimpoundment water quality will satisfy: (1) both inlake and release water quality objectives and (2) project purposes. Water quality conditions in similar reservoirs in the project area should be examined along with any design or operational modifications made or proposed to improve water quality conditions in these surrounding projects; this information should be included in the problem definition.

(1) Known factors. Factors that should be known at the beginning of the analysis, regardless of the engineering activity, are summarized in Figure 3-8. Reservoir and release water quality data will not be available for preimpoundment studies, but the remainder of the information can be compiled. Sources of information that should be consulted are indicated in Chapter 4.

(2) Factors to be determined. A number of unknown factors must be addressed during the water quality assessment to determine if reservoir water quality objectives can be attained. Typical unknown factors are summarized in Figure 3-9 and include:

(a) Inflow water quality conditions. Existing stream water quality conditions must be compared with applicable State and EPA criteria and standards during the preimpoundment assessment. If the existing stream water quality does not meet water quality criteria or standards, alternative designs or water control plans should be evaluated to minimize the impact of these violations on reservoir water quality.

(b) Stratification. The onset, duration, strength, and overturn of stratification dictate water quality conditions that may occur following impoundment. These conditions range from downstream temperatures that are

- Basin and reservoir geometry including elevation-area-capacity relationships for the reservoir.
- Hydraulic outlet design and geometry.
- Reservoir routings and operations data for the period of record under alternative water control plans.
- Existing stream water quality.
- Meteorological conditions within the basin from National Weather Service stations located as near the proposed site as possible.
- The locations and water quality characteristics of surrounding water bodies.
- Land use within the watershed.
- Existing reservoir water quality conditions.
- Existing reservoir release water quality conditions.

Figure 3-8. Project characteristics known prior to beginning a water quality study

- Inflow quality and inflow placement in the reservoir
- Inlake water quality conditions with emphasis on:
    - Temperature regime
    - DO regime
    - Algae concentrations and succession patterns
    - Withdrawal zone
- Release water quality conditions with emphasis on:
    - Temperature
    - DO
    - Metal concentrations (Fe, Mn)
    - Organics
    - NH_3 and H_2S

Figure 3-9. Typical water quality factors to be assessed in reservoir water quality studies incompatible with the water use objective to high iron concentrations in reservoir releases from an anoxic hypolimnion. Accurate stratification predictions are required to assess potential water quality concerns and develop appropriate management approaches.

(c) Dissolved oxygen regime. Determination of the hypolimnetic oxygen demand and depletion rates in conjunction with the strength and duration of stratification can indicate the potential for and duration of anoxic conditions. This may impact both inlake and reservoir release water quality.

(d) Inflow and withdrawal zones. Seasonal changes in the thickness and location of the inflow zone may influence the availability of inflowing nutrients to phytoplankton in the euphotic zone, contribute organic matter to the metalimnion or hypolimnion that may deplete DO in these two areas during microbial decomposition, or provide sufficient energy to create additional mixing and entrainment between the epilimnion and metalimnion or the metalimnion and hypolimnion. The thickness and location of the withdrawal zone may withdraw cold water; withdraw anoxic water; blend warmer, oxygenated water with hypolimnetic water; or entrain water from these stratification zones, which will influence release water quality. The inflow placement and withdrawal zones should be determined for an annual cycle.

(e) Productivity. Phytoplankton species assemblages, successional patterns, biomass, and chlorophyll concentrations must be estimated. This information may indicate potential problems for project purposes such as water supply (trihalomethane precursors, taste and odor, filter clogging), recreation (nuisance algal blooms, surface films), and fish and wildlife enhancement or mitigation. Primary productivity, as previously mentioned, may also influence secondary and tertiary (fish) productivity.

(f) Release quality. Release water quality should be determined and compared with downstream water quality objectives. Reduced constituents released from an anoxic hypolimnion can markedly influence downstream objectives. Oxidation of manganese (II), iron (II), and hydrogen sulfide; nitrification; and organic matter decomposition may exert an oxygen demand downstream in addition to violating stream water quality criteria and standards.

(g) Criteria and standards. Project purposes such as water supply, irrigation, recreation, and fish and wildlife conservation may be impacted if water quality criteria and standards are not satisfied. Both inlake and reservoir release water quality should be compared with applicable criteria and standards.

c. Assessment Techniques.

(1) The selection of appropriate techniques to assess the water quality of a proposed reservoir depends on the stage in project design, problem definition, and required resolution. All of the assessment techniques, with the obvious exception of field studies (since no reservoir exists), are

appropriate and have been used in preimpoundment water quality studies. Review of available information and similar studies on other projects, simple calculations, and analyses of existing water quality data should be conducted at all phases of project planning and design. The study objectives should determine the level of detail and accuracy required and used in the study.

(2) During the preliminary phase of project design, order of magnitude estimates may be sufficient to screen alternatives. If water quality data on the river and surrounding water bodies are not available, field studies should be designed and implemented to collect data on representative systems. As greater problem resolution is required, more detailed information, such as nutrient loading models, and statistical techniques, such as regression analyses or time series analyses, may be appropriate to provide mean annual estimates or seasonal estimates of representative water quality constituents.

(3) Advanced design considerations warrant the use of mathematical models for water quality prediction and the selection of final design and operation criteria to achieve water quality objectives. In addition, physical model studies may be required to define withdrawal zones, and laboratory studies may be required to determine chemical and biological process rates. These techniques have been used in combination to provide an integrated assessment of expected reservoir water quality in various preimpoundment studies.

3-5. Postimpoundment Assessment.

a. General.

(1) A postimpoundment assessment measures the reservoir water quality conditions that have occurred following construction. During the early postimpoundment period, the water quality characteristics are unstable; this period has been termed the trophic upsurge period. The duration and intensity of the trophic upsurge period vary among reservoirs due to factors such as geographic location (latitude), site preparation, and filling schedule.

(2) Reservoirs in the northern latitudes tend to have shorter trophic upsurge periods than reservoirs in southern latitudes.

(3) Site preparation can range from timber removal, through secondary vegetation removal and debris removal, to topsoil removal. Also, partial clearing between specific elevations and retention of timber in selected locations are sometimes part of site preparation. Additional site preparation often involves construction of drainage ditches to ensure that all marginal pools, sloughs, and depressions fluctuate freely with the main reservoir. All these activities must be included in the postimpoundment evaluation.

(4) In general, a postimpoundment assessment evaluates the physicochemical and biological changes during the trophic upsurge period using those specific diagnostic techniques identified in the preimpoundment assessment. It can serve as a basis for evaluating the adequacy and quality of the predictive

techniques used during the preimpoundment investigations. The postimpoundment assessment is important for guiding water control management during the transition phase following impoundment.

b. Expected Consequences. The expected consequences of a new reservoir include changes in water quality, which may deteriorate existing conditions (as discussed in Chapter 2), as well as changes in the aquatic biota of the original riverine system. Preimpoundment predictions and water quality conditions of surrounding reservoirs with similar structural designs and water control plans can provide comparative guidance as to when the trophic upsurge period is over.

c. Program Study Definition. The two major concerns associated with postimpoundment conditions involve whether: (1) the transitional reservoir water quality following impoundment is satisfying inlake and release predictions and objectives and project purposes, and (2) post-transitional water quality will meet project purposes. Any design or operational modifications made or proposed to improve the temporary water quality conditions in the reservoir should be reviewed and incorporated in the program or study definitions.

(1) Known factors. The known factors at the beginning of the program or study are the same as those identified for preimpoundment assessments. Knowledge of existing water quality and release water quality includes inflow quality and placement in the reservoir, inlake water quality conditions (water temperature regime, DO regime, algal concentration and succession patterns, and withdrawal zone), and release water quality conditions (water temperature; DO; metals (Fe and Mn) concentrations; and organics, NH_3 and H_2S). (See the discussion on preimpoundment assessment (para 3-4) for a further description.) The water quality of both inlake and reservoir releases should be compared to applicable criteria and standards.

(2) Factors to be determined. The postimpoundment water quality conditions must be compared with applicable State and EPA criteria. The unknown factors that must be addressed during the postimpoundment period to determine if reservoir water quality objectives can be attained are discussed briefly below.

(a) Inflow water quality. Alternative water control plans should be considered when the existing inflow stream water quality does not meet state or Federal water quality criteria.

(b) Stratification. The establishment, duration, and strength of stratification and occurrence of overturn will play a major role in the other physicochemical and biological conditions that may occur following impoundment. The initial filling rate criterion and the hydrologic condition will determine if a reservoir is partially or completely filled in one storage season. The amount of water stored during the first filling season, and the length of ti necessary before reaching full-pool conditions, will play a dominant rol the water temperature stratification characteristics during the trophic upsurge period.

(c) Dissolved oxygen regime. The hypolimnetic oxygen consumption rate of a new reservoir will be determined by such factors as the size of the hypolimnion, water retention time, the amount of biodegradable organic material available, and the water temperature. In new reservoirs that have large hypolimnia, are cleared of organics, have moderate to long retention times (30 to over 365 days), and have hypolimnion water temperatures between 4° and 8° C, the hypolimnetic oxygen consumption rates tend to be linear. New reservoirs that have small hypolimnia, are cleared of organics, have long or short retention times, and have hypolimnion water temperatures above 8° C can exhibit hypolimnetic oxygen consumption rates that have polynomial decay characteristics. New reservoirs also can exhibit oxygen depletion higher in the water column, usually in the metalimnion region, due to microbial decomposition. This occurrence is often most apparent in the lacustrine zone near the dam.

(d) Inflow and withdrawal zone. Changes in the thickness and location of the inflow zone can change several factors important to water quality considerations. Energy that creates additional mixing and entrainment, nutrient availability to the euphotic zone, and organic contribution to the metalimnion and hypolimnion can become important unknown factors for postimpoundment programs or studies. The thickness and location of the withdrawal zone also can change several factors important to water quality. Release water quality is affected by the withdrawal of cold water, anoxic water, or blended water. The characteristics of the inflow placement and the withdrawal zones, therefore, are important factors to be determined at new reservoirs.

(e) Productivity. Phytoplankton species, patterns, biomass, and chlorophyll concentrations should be determined at new reservoirs. Potential problems that could affect project purposes such as water supply, recreation, and fish and wildlife should be identified. Phytoplankton present at a new reservoir can be different from those present in a mature impoundment.

(f) Release quality. The quality of the water being released from a reservoir should be determined and compared with downstream water quality objectives, State standards, and/or Federal criteria. Constituents such as manganese, iron, hydrogen sulfide, and ammonia released from an anoxic hypolimnion can markedly influence downstream objectives.

d. Assessment Techniques. Selection of appropriate analytical techniques to evaluate reservoir water quality conditions are usually determined before postimpoundment fieldwork is initiated. There will be heavy reliance on field observation and data collection as the diagnostic technique in this phase. Data evaluation techniques used in the preimpoundment studies are usually appropriate. However, during some phase of the postimpoundment program or study, it may be necessary to introduce new analytical techniques that would indicate unanticipated water quality developments. Simple calculations and analyses of existing data should be conducted at all phases of the postimpoundment program or study. Regression analyses or time series analyses may be appropriate to provide seasonal or annual estimates of the important water quality constituents.

3-6. Operational Monitoring. Operational monitoring is implemented to establish baseline water quality conditions and changes, identify water quality problems, provide guidance to water control elements for effective water quality control, and provide a database for coordination with other agencies. In general, operational monitoring is long term and should cover the life of the project. Assessment occurs with each set of data collected to evaluate short- and long-term trends and/or changes.

a. Expected Consequences. The consequences of operating a reservoir range from meeting all water quality objectives to not meeting any objectives. If the water quality assessment indicates no problems, then no action is required. If a water quality problem is encountered or predicted, a remedial or corrective course of action may be recommended and may include a change in water control facilities and/or the water control plan. Data collected under these programs are used in a variety of applications and serve as a valuable database for other types of studies (e.g., recreation planning, drought contingency, change in project purpose).

b. Problem/Study Definition. The major question associated with operational monitoring regards the effectiveness of the project in meeting water quality objectives. If a project is not attaining water quality goals, operational monitoring should reveal the first evidence of a problem. The monitoring program should be broad enough in scope to identify potential problems in any major area (trophic status, contaminants, recreation, etc.) and yet remain cost effective. Once a problem has been identified, other types of studies should be initiated to define alternatives.

(1) Known factors. Known factors about the reservoir should include morphologic type (dendritic, prismatic, etc.) and features, hydrologic record, and operational plans and constraints. Knowledge of the watershed characteristics and activities should provide a general indication of inflow water quality. Once a project has become operational and water quality monitoring begins, a database will be available for comparative analyses.

(2) Factors to be determined. The unknown factors involved in an operational monitoring program are numerous but may be classified as either definable or undefinable. Definable factors are those water quality characteristics which through the monitoring program may be identified and, if necessary, modified. Undefinable factors are those that may impact the water quality but only the symptom or effect is observed. For example, a fish kill may result from oxygen depletion or viral infection. If immediate sampling is not conducted, there may be no measurements to indicate the cause of the fish kill.

c. Assessment Techniques. The method of analysis depends on the type of reservoir, operational scheme, anticipated water quality problems, and water quality objectives. The monitoring will usually involve field studies and may include other types of studies. Data collected should be examined for deviations from Federal or State criteria and in regard to eutrophication aspects as well as recreation interests. Data interpretation should be made in relation to project objectives and reported in accordance with ER 1130-2-334 (see Chapter 4). Alternatives identified as a result of operational monitoring must be reported to the appropriate responsible element.

3-7. Modification of Operations. A typical nonstructural modification may be an operational change. Operational modifications generally involve changing the reservoir water control plan or guide curve. This modification may be proposed because of in-reservoir uses, reduced volume of the reservoir caused by sedimentation, or downstream water uses. Prior to modifying a guide curve, however, potential impacts on reservoir water quality should be assessed.

a. Expected Consequences. The expected consequences of the proposed modification are related to the change in pool elevation, surface area, and reservoir volume. A small increase in pool elevation may have minimal impact on reservoir water quality since the shallow water column over the newly inundated areas will probably not become anoxic. Large pool elevation changes, however, can significantly modify the depth, surface area, volume, and residence time of the reservoir and, as a result, may have a significant impact on reservoir water quality. As a result of these changes, the epilimnetic and hypolimnetic volumes may increase during periods of stratification. The location of the thermocline may rise in elevation but remain about the same distance below the water surface as in the existing reservoir. Reservoir water quality may be degraded during the first 6 to 10 years following an increase in storage (transition period) due to the inundation of terrestrial vegetation and organic soil. Substantial water quality changes may occur if the hypolimnetic DO is depleted due to this change. The length of the anoxic period influences the magnitude and types of water quality changes that occur. Some natural hypolimnetic aeration may occur when oxygenated interflows or underflows enter the hypolimnion, but the oxygen carried in these flows is generally insufficient to satisfy the hypolimnetic oxygen demand if the reservoir residence time is relatively long.

b. Program/Study Definition. The initial program or study is to determine the potential for water quality changes as a function of operational modifications. Small pool elevation changes or minimal phase changes in the rule curve may have no significant impact on reservoir or release water quality. However, large pool elevation changes may result in extensive mudflat formation, inundation of terrestrial areas, and altered reservoir and release water quality. If large pool elevation changes occur, water quality problems may be similar to those encountered in proposed impoundment studies since terrestrial areas could be inundated. Changing release depth, however, may result in water quality problems similar to those encountered with structural modifications. A review of other District projects with a similar operation may produce better problem definition and resolution.

(1) Known factors. Factors for which information should be available at the beginning of the analysis are listed in Figure 3-8.

(2) Factors to be determined. The unknown factors related to operational modifications are indicated in Figure 3-9 and are similar to those discussed for structural modifications.

c. Assessment Techniques. Information on similar operational modifications and observed water quality conditions should be reviewed and simple calculations performed to determine changes in residence times, stratification potential, shoreline development ratios, and other similar factors. Nutrient loading models may indicate increased or decreased inlake nutrient concentrations, hypolimnetic oxygen demand, chlorophyll concentrations, transparency estimates, and trophic state classification provided the change in storage is significant. Mathematical models provide an effective means of evaluating a number of operational alternatives. Physical and mathematical models can provide information on changes in reservoir hydrodynamics under several hydrologic and regulation regimes. Laboratory and modeling studies can be used to indicate potential anaerobic problems that may occur with an increase in storage and inundation of a terrestrial area.

3-8. Modification of Water Control Structures. Typical structural modifications include the addition of a submerged weir or selective withdrawal capabilities to improve inlake and/or downstream water quality.

a. Expected Consequences. The expected consequences are a function of the purposes for modifying the structure. Addition of selective withdrawal to a structure with bottom sluice gates to meet a natural downstream temperature objective may result in: stronger stratification profiles throughout the pool, a longer stratification period, colder hypolimnetic temperatures, longer hypolimnetic residence times, greater potential for an anoxic hypolimnion, increased surface discharge, cooler surface temperatures in the spring and early summer, a possible shift in phytoplankton succession with the altered thermal regime, and potential shock loading on the downstream system if the bottom sluice gates must be used to pass stormflows. Addition of a submerged weir to a bottom sluice gate structure may result in: greater surface discharge; a shallow, cooler epilimnion and a larger, colder hypolimnion; an anoxic hypolimnion; shift in phytoplankton succession; low DO throughout the pool at overturn; and a longer stratification period. Similar modifications made in other projects should provide insight into the expected consequences in the prototype.

b. Program/Study Definition. The primary problem is to determine if the structural modifications can satisfy downstream water quality objectives and maintain or enhance reservoir water quality. One hydraulic outlet design may improve reservoir water quality while an alternative design may improve release water quality. Structural modifications should be selected to minimize the impact on reservoir project purposes but to attain inlake and downstream objectives. Operational considerations must be included as part of the design criteria. A major problem with many selective withdrawal structures is that the inlet portals are not designed to pass large flows and the bottom floodgates must therefore be used to pass storm events. This change in withdrawal depth may result in shock loading of cold water, which is potentially low in DO and high in nutrients and other constituents, to the downstream system.

(1) Known factors. Factors that should be known at the beginning of the assessment are listed in Figure 3-8. An additional factor that should be known is any operational problems associated with structures similar to the proposed hydraulic design.

(2) Factors to be determined. Several unknown factors that need to be assessed to evaluate the effectiveness and impact of the structural modification are summarized in Figure 3-9 and include:

(a) Criteria and standards. The sources or causes of violations in water quality criteria and standards must be identified and used to evaluate the effectiveness of the proposed structural modification in improving the water quality conditions. Some hydraulic outlet designs may be more effective in minimizing certain conditions than other designs.

(b) Stratification. Since the general intent of many structural modifications is to meet a downstream temperature objective, it is important the thermal regime in the pool be accurately predicted.

(c) Inflow and withdrawal zones. An altered thermal regime can influence or alter the inflow and withdrawal zones. Inflow placement and withdrawal zones are directly influenced by the density distribution within the pool. Accurate predictions of withdrawal zones are required to determine if a downstream temperature objective can be met.

(d) DO regime. Stronger stratification may diminish reaeration across the metalimnetic interface and result in an anoxic hypolimnion. Stronger stratification may also result in oxygenated stream inflows proceeding as interflows, further reducing hypolimnetic oxygen supplies. Development of an anoxic hypolimnion may result in entraining and/or discharging higher concentrations of phosphorus, ammonia, manganese (II), iron (II), and hydrogen sulfide in the reservoir releases. The impact of the structural modification on the DO regime in the pool and the potential for anoxic conditions may alter proposed hydraulic designs and operational plans.

(e) Productivity. Biological and chemical reaction rates are temperature dependent, so an altered thermal regime may result in changes in the phytoplankton community and higher trophic levels. Increased nutrient concentrations associated with an anoxic hypolimnion may be entrained in the mixed layer and promote increased productivity. Additional surface discharge may result in higher mixed-layer nutrient concentrations and also stimulate additional productivity. Changing the temperature and depth of the mixed layer may alter the successional pattern of the phytoplankton community, reducing or intensifying problem algae such as blue-green bacteria.

(f) Release quality. Structural modifications are generally used to meet a downstream release target for flow, temperature, DO, or other objectives. The predicted release quality, therefore, must be compared with the downstream objective. For a constituent such as DO, it is also important to consider the impact farther downstream. While the releases may be saturated with DO from reaeration in the conduit, chemical and biological oxygen demands associated with various release constituents may create an oxygen deficit and sag farther downstream. Oxidation of hydrogen sulfide, iron (II), and manganese (II); nitrification; and organic decomposition of release constituents, particularly from an anoxic hypolimnion, should be considered and routed downstream to assess their impact on the downstream aquatic community.

c. Assessment Techniques. Information on the impact of similar hydraulic designs and operation plans on reservoir water quality should be compiled and simple calculations performed. Since the structural modification primarily influences the zone of withdrawal and not the flow rates, nutrient loading models may not be as appropriate as other techniques since the surface area, volume, total nutrient loading, hydraulic loading, and residence time are not changed by modifying the zone of withdrawal. Determination of the design of the selective withdrawal structural and the resulting reservoir and release water quality should include a reservoir water quality model. Selection of a specific model should consider other reservoirs in the system, the interaction of the reservoirs, the need for stream simulations, and the degree of detail required in the water quality simulations. Physical models may help describe changes in withdrawal zones resulting from the structural modification. Laboratory studies may be required to modify model reaction rates for changes in nutrient and anaerobic processes.

3-9. Specific Water Quality Problems. Any number of examples could be discussed. The example used in this discussion is a bridge construction project causing a local constriction in a reservoir.

a. Expected Consequences. Two major consequences can be expected to occur as a function of the constriction: acceleration of flow through the localized area and a backwater effect upstream of the constriction. The basic hydraulic relationship, $Q = AV$, indicates that a reduction in cross-sectional area A must be compensated by an increase in velocity V in order to continue to pass a given flow Q. A localized constriction reduces the cross-sectional area so the velocity at a constant flow rate increases in the constriction. This localized velocity increase may disrupt stratification and produce a well-mixed zone in this area. The localized constriction may also create a backwater effect upstream, resulting in increased sedimentation of both inorganic and organic suspended solids. Depending on the stratification pattern and hypolimnetic volume, this increased organic deposition may result in sufficient oxygen demand to promote anoxic conditions. Increased sedimentation can result in loss of storage volume in this upstream area.

b. Problem Definition. The location of the bridge site is important if upstream water quality conditions are to be maintained. Location of a constriction near the headwater may result in extensive mudflat formation upstream from the bridge. This area can be highly visible to bridge traffic. Sampling stations need to provide information that is representative of the general water conditions in the pool and near the proposed bridge site. Location of these sampling sites at points where bridges cross a reservoir, while convenient, may not represent water quality within the pool and may result in erroneous conclusions concerning existing reservoir water quality conditions.

(1) Known factors. Information available at the initiation of the impact assessment should include (Figure 3-8):

(a) Reservoir geometry including shoreline configuration and cross-sectional areas.

(b) Sedimentation survey results including areas of erosion and deposition, relative sedimentation rates, and specific transect geometry.

(c) General circulation patterns, residence times, flow regime, sediment loads, trap efficiency, outflow sediment concentrations, and operation records.

(d) Existing water quality prior to modification, including stratification profiles, thermal regime, and nutrient and organic loading and retention.

(e) Release water quality and downstream objectives.

(2) Factors to be determined. There are several unknown factors that must be addressed to assess the impact of the proposed modification (Figure 3-9). These factors include:

(a) Backwater effects. The backwater effects of the construction need to be assessed to determine the extent of the upstream effects and potential areas of impact.

(b) Sedimentation. Previous sediment loads and sedimentation records need to be used to predict the sedimentation regime following reservoir constriction. This should include both inorganic and organic suspended solids.

(c) Stratification. The upstream and downstream stratification patterns should be estimated following constriction.

(d) DO regime. Increased organic sedimentation upstream of the constriction may produce additional oxygen demand due to increased microbial decomposition of this organic matter. Stratification may result in the development of an anoxic hypolimnion and the resolubilization and release of nutrients and metals into the overlying water column.

(e) Nutrient regime. Increased sedimentation and decomposition of particulate organic matter may increase nutrients upstream of the constriction.

(f) Productivity. Increased nutrient concentrations may promote and stimulate phytoplankton production, resulting in nuisance algal blooms.

(g) Lower reservoir. The influence on reservoir water quality downstream of the constriction also needs to be assessed. Water quality conditions may significantly improve downstream with the removal of inflowing sediments, nutrients, and organic matter. Increased light penetration downstream, however, may also enhance phytoplankton productivity and create other conditions such as taste and odor, surface films, and unaesthetic conditions.

(h) Release quality. The location of the constriction may improve release water quality if the majority of the particulates are removed prior to discharge downstream. A location near the outlet tower, however, may minimize control over release quality and result in diminished release water quality.

c. Assessment Techniques. Existing information on the effects of flow constrictions can be found in most hydraulic engineering texts (e.g., Ref. 74). Existing water quality data collected from areas where localized mixing may occur should be reviewed carefully to avoid erroneous conclusions. Remote sensing has been used to analyze surface turbidity plumes and can provide qualitative evidence of local acceleration and sedimentation in other similar projects. Physical and two-dimensional numerical models can indicate changes in flow, backwater effects, and circulation patterns due to constriction and may indicate the potential for destratification if a stratified two-layer system is used. Mathematical sediment transport and water quality models can be used to predict sedimentation rates and patterns, hypolimnetic oxygen depletion rates, nutrient cycling, and productivity upstream and downstream from the constriction, including release water quality.

CHAPTER 4

WATER QUALITY ASSESSMENT TECHNIQUES

4-1. Scope. This chapter describes techniques available for assessing reservoir water quality conditions. There is a hierarchy of available techniques that reflects not only increasing requirements of time, cost, and technical expertise, but also accompanying increases in the degree of understanding and resolution of the problem and its causes. This hierarchy includes screening, diagnostic, and predictive techniques, which are described in Sections I through III, respectively.

Section I. Screening Techniques

4-2. General. Screening procedures can be used initially to determine the existence of a problem, identify applicable assessment techniques, and suggest probable assessment approaches. Screening should be performed for all water quality assessments since it provides the necessary background information for the diagnostic or predictive techniques that follow.

4-3. Information Search. An information search is the compilation of existing hydraulic, hydrometeorologic, and water quality data, both site specific (General Design Memorandums, Design Memorandums, Water Control Manuals) and non-site specific (watershed or regional reports). An information search is used to identify existing knowledge about the project water quality. In addition to readily available published sources, valuable information can be obtained from local sources such as newspaper articles; university reports; county extension agents; commercial fisherman or other commercial users of the reservoir; State sources such as departments of agriculture, environmental protection, fish and wildlife, geological survey, soil conservation, and transportation; and comparable Federal agencies. Most Federal reports can be obtained from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Va. 22161.

a. Applicability. An information search should be the first step and an integral part of all reservoir water quality studies to minimize costs and time and to prevent duplication of existing studies or redevelopment of proven techniques. A major assumption of information searches is that knowledge obtained from other studies is applicable for project water quality concerns. The major limitation is identifying the proper individual(s) to contact. In many instances, only one individual may be aware of a particular study that contains the pertinent information. Water quality specialists in the Corps Division offices and at the Office, Chief of Engineers (DAEN-CWH-W), can provide guidance in the information search.

b. Implementation and Interpretation. Local information is obtained by contacting as many people and agencies as possible. Many Federal agencies, such as the US Fish and Wildlife Service, have information specialists assigned to collate and distribute information upon request. State and local information generally can be obtained only through personal contact. Initial contacts can be obtained from the US Geological Survey (USGS) NAWDEX Directory for Membership Organizations (Ref. 47). Generally, stream discharge and quality data are available from the USGS (WATSTORE), stream and lake quality data are available from EPA (STORET), and meteorological data are available from the National Weather Service. Literature searches can be initiated quickly and effectively using computerized literature databases (Figure 4-1). These databases contain literature sources ranging from textbooks, to scientific and engineering journal articles, to NTIS reports. A user identification number can be obtained from one of several commercial literature database vendors, or a literature search can be conducted by Corps libraries, including the WES Technical Information Center Library. Keywords used in the literature search must be judiciously selected to avoid superfluous literature.

4-4. Project Characteristics and Calculations.

a. Description. The general project characteristics and simple calculations or order of magnitude analyses that may be important for water quality studies are presented in Table 2-2 and discussed in Appendix D. In general, these include:

(1) Watershed characteristics. The drainage area, annual average runoff rates, average basin slopes, land use designations, and erosion potential are some characteristics that may impact reservoir water quality. In addition, other watershed characteristics that influence constituent loadings to reservoirs need to be identified and summarized.

(2) Reservoir morphometry. Morphometric characteristics such as reservoir mean and maximum depth, surface area, volume, length, shoreline development ratio, and fetch should be compiled.

(3) Hydromorphometric interactions. Simple calculations or order of magnitude analyses include computations of theoretical hydraulic residence times, densimetric Froude numbers for stratification potential, destratification potential, areas of potential reservoir sediment erosion or accumulation, plunge point depth, and other similar calculations.

b. Applicability. General reservoir and watershed characteristics and simple calculations are useful in identifying potential water quality concerns, initially evaluating reservoir water quality with respect to criteria and objectives, comparing and contrasting observed water quality in different reservoirs, screening other assessment techniques, and screening potential control or management techniques or procedures. The summary characteristics and calculations are estimates predicated on general causal and rule-of-thumb relationships and therefore may not have the depth and detail suitable for design. These procedures are limited to generalizations concerning potential reservoir water quality problems or processes. No estimates of uncertainty or error are associated with the summary characteristics, so the reliability of the predictions may be unknown or limited.

- Bibliographic Retrieval Services (BRS)
  1200 Route 7, Latham, NY 12110
  Telephone: (800) 833-4707
  Service provided on an annual subscription basis.

- BRS at NIGHT
  1200 Route 7, Latham, NY 12110
  Telephone: (800) 833-4707
  Lower cost service, available only at night.

- Dialog Information Services, Inc. (DIALOG)
  3460 Hillview Ave., Palo Alto, CA 94304
  Telephone: (800) 227-1600
  Service is provided on a per use basis with no initial fees. Largest selection of databases.

- Knowledge Index
  3460 Hillview Ave., Palo Alto, CA 94304
  Telephone: (800) 227-1600
  Lower cost DIALOG services, with initial fee charged.

- System Development Corporation (SDC ORBIT)
  2500 Colorado Ave., Santa Monica, CA 90406
  Telephone: (800) 421-7229
  Service is provided on a per use basis. Initial fee covers online training time.

Figure 4-1. Selected information retrieval services
(Source: Ref. 91)

c. Implementation and Interpretation. Steps in implementing this approach include:

(1) Data collation. Data on watershed and reservoir characteristics can be obtained readily from USGS topographic maps, Soil Conservation Service (SCS) erosion studies, District reservoir and sedimentation surveys, land use classifications conducted by EPA and State organizations, and General Design and Feature Design Memoranda and other project documents. Stream and watershed data may be available from State geological surveys and environmental protection agencies and from other governmental organizations, universities, local citizen groups, or private firms.

(2) Calculations. All calculations require no more than a hand calculator. In addition to the order of magnitude estimates for water quality included in Appendix D, additional formulas can be obtained from Refs. 32, 60,

62, 63, and 78. Any procedure that will permit a better understanding of potential water quality conditions or appropriate assessment techniques should be incorporated in the analysis.

(3) Interpretation. The reservoir and basin morphometry, hydrometeorology, and other physical factors are important in the development of seasonal patterns in reservoir water quality. For example, a large drainage area to reservoir surface area ratio indicates the potential for significant sediment and nutrient loading, while a short theoretical hydraulic residence time indicates the potential for significant transport and exchange. A large shoreline development ratio computed from a dendritic reservoir with many coves and embayments indicates high biological productivity since productivity is normally higher in littoral zones that in pelagic regions of a reservoir. More detailed information on the use and interpretation of these simple indices can be found in Appendix D.

4-5. Site-Specific Water Quality Data. Site-specific water quality data include all the data collected in the reservoir, the reservoir tributaries, and the tailwater, including downstream stations.

a. Applicability. Analyzing site-specific water quality data is the most appropriate technique for assessing reservoir water quality. Samples collected at various locations within the reservoir through time may describe the temporal variations, spatial size, duration, and frequency of water quality conditions. Site-specific water quality data collected from a well-designed and well-implemented data collection program can be used to confirm or refute perceived concerns, indicate the effects of historical trends or changing land use on water quality, and indicate control or management alternatives to achieve water quality objectives.

b. Implementation and Interpretation. It is assumed that the water quality samples were collected and analyzed using approved methodology and are therefore representative of actual reservoir conditions. Uncertainty and variability estimates generally are not available because of lack of replication or split sampling and must be assumed based on local experience and textbook values.

Section II. Diagnostic Techniques

4-6. General. Once the study objectives and/or water quality conditions are defined, diagnostic techniques can be used to determine the cause of these conditions. Application of these techniques is not mandatory if the cause of the condition is not a concern or is already known.

4-7. Field Investigations. Field investigations include studies in four general categories: inflow, intensive field investigations, water quality monitoring, and tailwater studies. Similar procedures may be used in all four categories, but the objectives, application, and, therefore, interpretation may differ among categories.

a. Inflow Studies. The impact of dissolved and suspended materials transported by inflow on reservoir water quality depends not only on the concentrations of the materials present but also on how the inflow behaves as it enters, moves through, and mixes within the pool. To study this behavior, a natural tracer, such as specific conductance, or an artificial tracer is followed as the inflow progresses into and through the pool. A reliable tracer that is easy to use is Rhodamine WT, a commercially available fluorescent red dye. The movement and mixing of an inflow as it moves into the pool have been studied (Refs. 11 and 12).

(1) Applicability. Inflow field investigations can be used to determine flow conveyance zones (both vertical and lateral), circulation patterns, and plunge point locations and to quantify travel times and dilution rates. The results of inflow field studies can also be used in the calibration and verification of simulation transport models. When a natural tracer or dye is used in an inflow field investigation, it is assumed to be a conservative material (i.e., does not decay or is not readily adsorbed onto vegetation or bottom sediments) with fluid properties similar to those of water. The fluorescence of Rhodamine WT dye is affected by temperature, pH, chlorine, and salinity, but only the effect of temperature can be easily compensated. There is evidence that diethylnitrosamine (DENA), a known carcinogen, is formed when Rhodamine WT is used in nitrite-rich waters; thus, its use should be restricted in nitrite-rich waters. Inflow studies can be manpower and equipment intensive while extrapolation of study results may be limited to similar hydrometeorological conditions.

(2) Implementation and interpretation. Coordination of manpower and equipment is essential during the sampling effort to ensure that proper data are collected. This is usually not a problem when the study is conducted under base flow conditions since the time-of-travel of the tracer is relatively slow when compared to travel times during and following storm events. However, storm events transport significantly more suspended solids, nutrients, and bacteria into reservoirs than do base flows and may have a significant impact on reservoir water quality. The procedure for implementing an inflow field study is as follows:

(a) Step 1. Reconnaissance of the study site for possible causes of interference with the tracer analysis (e.g., background fluorescence, turbidity, chemical discharges).

(b) Step 2. Injection of the dye tracer into the flow at a location far enough upstream of the pool to ensure complete vertical and lateral mixing.

(c) Step 3. Collection of samples from the study area.

(d) Step 4. Analysis of the samples to determine relative tracer concentrations.

(e) Step 5. Data analysis, including a mass balance of the tracer (determination of percentage of dye recovered) and graphic presentation of the results where applicable (cross-sectional and longitudinal profiles of dye concentration and temperature). Generalizations should not be made from a single study without detailed consideration of flow regime, stratification patterns, meteorology, and project operation.

b. Intensive Field Investigations. Intensive field investigations are studies conducted over a short period of time to analyze specific processes affecting reservoir water quality, such as sediment oxygen demand; water movements and constituent transport during hydropower generation; or the spatial distribution and diel patterns of water quality constituents within a reservoir. Intensive field investigations differ from monitoring activities in their objectives, design, and sampling effort.

(1) Applicability. Intensive field studies quantify processes that directly influence reservoir water quality. These processes may occur during a short period of time, such as storm events. Intensive studies also provide more reliable estimates of process rates. These studies are appropriate for highly variable processes such as sediment transport, sediment oxygen demand, algae blooms, or processes occurring during a hydropower generation cycle. Reliable estimates of many process rates are essential to diagnose the causes of water quality concerns and evaluate management alternatives. It is assumed that a particular technique does not alter or modify the process under investigation and that the measured rates are indicative of the rates under natural conditions. Techniques that confine or restrict water movement or exchange, such as biochemical oxygen demand (BOD) bottles, plastic spheres, or limnocorrals, may alter or modify the specific rate processes under investigation. It is also assumed the processes are representative (with appropriate temperature or other corrections) for other time intervals.

(2) Implementation and interpretation. Implementation of these techniques should consider:

(a) The important processes influencing a specific water quality condition.

(b) The site-specific characteristics and their applicability for a given process, their previous use, and associated problems.

(c) Any special equipment, technical expertise, or analytical capabilities required for satisfactory implementation.

(d) The estimated longitudinal, lateral, and vertical variability of processes and rates within the reservoir for assessing the uncertainty or reliability of rate estimates.

(3) Estimates of error. Error or variance estimates can identify areas of the reservoir where rate estimates are reliable with a small standard

error; these estimates can also be used to define areas where process rates have large standard errors and require additional sampling for more accurate estimates.

c. Water Quality Monitoring. Water quality monitoring is a sampling program designed to investigate seasonal and annual trends in reservoir water quality. The water quality constituents monitored may range from in situ variables such as temperature, DO, specific conductance, and pH, to chemical constituents such as nutrients (nitrogen and phosphorus species) or trace elements, contaminants (PCB's, mercury, etc.), and biological constituents (chlorophyll, phytoplankton, benthos).

(1) Applicability. Monitoring programs are appropriate for assessment of short- and long-term trends in water quality, early identification and evaluation of potential water quality problems, and evaluation of the effectiveness of management approaches. If properly designed and implemented, monitoring programs can be the most efficient, cost-effective approach for assessing reservoir water quality.

(2) Implementation and interpretation. The major assumption of monitoring programs is that data collected on specific sampling dates at specific stations are representative of water quality conditions that are continually occurring through time and throughout the reservoir. Interference or sampling artifacts are assumed to be minimal. Horizontal and vertical gradients exist for nearly all reservoir water quality constituents and should be accounted for in the sampling program design and subsequent data evaluation.

d. Tailwater Studies. Tailwater investigations are generally concerned with three generic problems: minimum flow requirements, large flow variations, and the impact of reservoir release quality on downstream uses and the downstream biotic community.

(1) Applicability. Minimum flow requirements and release quality may be associated with all project types, while frequent large flow variations are usually associated with hydropower projects. The effects of reservoir releases on tailwater quality are discussed in Chapter 2, Section IV. Field investigation represents the most applicable technique for tailwater studies. A majority of predictive techniques are directed at instream or low-flow requirements. The major assumption of low-flow techniques is that flow is primarily responsible for maintaining a viable tailwater system. Other factors such as water quality and biological interactions are not assumed to play a dominant role. Instream flow methodology may be of limited use if the downstream system is not controlled or regulated by flow. Instream flow methods may also be of limited use in assessing large flow variations. Although elevated flow may affect the downstream system, instream flow methodology is concerned primarily with minimum low flows.

(2) Implementation and interpretation.

(a) A number of instream flow techniques are available to assess water quality; these techniques range from desktop calculations to computer simulation models. Selected instream flow assessment methods are listed in Table 4-1. Selection of an appropriate method depends on the specific questions or problems addressed, data availability or requirements, habitat characteristics, and temporal considerations. Techniques for evaluating the effects of release water quality or large flow variations have been developed (Refs. 17, 25, and 27).

(b) The impact of reservoir releases on the downstream systems should be interpreted considering factors such as stream order; seasonality; flow attenuation; altered temperature, nutrient, and energy regime; and the critical time periods for the biotic community. Upstream or nearby stream systems may be of lower stream order than the reservoir tailwater system and thus might not reflect similar flow or energy regimes for comparison. The study time frame needs to be interpreted with respect to the critical time periods for the downstream biotic community and related to operational constraints that may also exist during this period.

4-8. Laboratory Studies. Laboratory studies are conducted under controlled environmental conditions to evaluate specific water quality processes or biotic responses to a specific set of conditions or treatments. Three laboratory techniques commonly employed to evaluate these responses--bioassays, microcosms, and soil-water reaction chambers--are described below.

a. Bioassay. A bioassay is any test that uses organisms to detect the presence of or measure the effect of one or more constituents. The tests are usually conducted with one or more biological species. Two types of bioassay techniques are algal bioassays, used to evaluate phytoplankton response to several nutrient levels, and toxicity bioassays, used to evaluate organism responses to potentially toxic constituents or compounds. These bioassays may be static, where the medium is not replaced throughout the test, or continuous flow, where the medium is continuously renewed.

(1) Applicability. The bioassay is appropriate in determining the concentrations of environmental factors to maintain aquatic life, the stimulatory or toxic levels of various constituents, or the effects of synergistic or antagonistic interactions among physicochemical variables on biotic responses. Bioassays are useful in evaluating the limiting nutrient, testing toxicity, and determining species-specific responses. The organism is assumed to respond to treatment in nature as it responds in the laboratory. It is also assumed that the treatment conditions are similar to the prototype environmental conditions. Separate tests are required for various test organisms or species, which may limit the applicability of results. Toxicity or biostimulation bioassay results for selected species may not provide exact information for other species. Test results may be reliable only under identical

TABLE 4-1

Summary of Existing Instream Flow Assessment Methods

Method	Characteristics Stream Flow Records	Hydraulic Simulation	Habitat Rating	Transect Data[1]	Species or Seasonal Specificity
Fixed percentage (e.g., Montana)	Yes	No	No	None	Little or none
Constant yield (e.g., NEFRP)	Yes	No	No	None	Some seasonal
Flow duration	Yes	No	No	None	Some seasonal
USFWS habitat evaluation	No	No	Some indirect	Single or multiple	Some species
Stage-discharge analysis (e.g., R-2 cross)	No	Yes (Manning's Eq.)	Indirect	Single v/d	No
WSP simulation (Idaho)	No	Yes (WSP)	Indirect (wetted perimeter)	Multiple v/d	No
Usable width (Oregon and modifications)	No	No	Yes	Single v/d	Yes
Preferred area (California and Washington)	No	No	Yes	Multiple v/d/s	Yes
PHABSIM (Instream Flow Group's Incremental Methodology and modifications)	Some	Yes (WSP or IFG4)	Yes	Multiple v/d/s/c/t	Yes

SOURCE: Ref. 87.

[1] v = velocity; d = depth; s = substrate; c = cover; t = temperature.

environmental conditions. Synergistic or antagonistic effects may not be considered.

(2) Implementation. Procedures for conducting bioassays are documented in a number of sources (Refs. 24, 48, and 50). Laboratory results should be analyzed through the use of standard statistical tests to evaluate difference.

b. Microcosms. Microcosms are enclosed experimental systems that have characteristics in common with both bioassays and field studies. Microcosm studies may involve more than one species or more than one trophic level and are intended to be more representative of the ecological process than single-species bioassay techniques. Microcosm studies range from small laboratory flasks to laboratory flumes.

(1) Applicability. The microcosm approach is often used to evaluate process rates for the transfer, accumulation, and assimilation of elements or compounds in aquatic systems. The microcosm provides greater information on the potential fate of materials introduced into the aquatic system. Microcosm testing can be done over a period long enough to evaluate the natural degradation of materials, as well as the impact on various stages of an organism's life cycle or impacts on several species simultaneously. It is assumed that organisms in microcosms respond similarly to organisms in an unrestrained environment and that all factors in the prototype system that could modify the organisms' response have been included in the microcosm. The results of a particular study may only be valid for the particular set of environmental factors tested. Conditions of the natural environment not considered may modify organism response.

(2) Implementation and interpretation. The microcosm approach must be based upon processes and/or organisms found in or expected in the prototype. Particular attention must be directed toward accurate representation of abiotic constituents of the water and sediments as well as species composition. The use of laboratory columns and chambers has been discussed by Barko et al. (Ref. 6) and Gunnison et al. (Ref. 70). Differences among process rates may be a function of the specific methodology as well as various treatment levels. Although microcosms are generally more representative of processes and rates occurring in the prototype system than bioassays, the physical, chemical, and biological interactions are occurring within an enclosure that may confine and influence these interactions. The variance associated with the rate measurements should be formally estimated and used to assess the uncertainty and reliability of the rate estimate.

c. Soil-Water Reaction Chambers. Soil-water reaction chambers are 250-liter Plexiglas columns capable of holding 15-centimeter-deep blocks of soil occupying the area of approximately 0.2025 square meter (Ref. 70). A water column of 210 liters is placed on top of the soil in the chamber. The reaction chambers are equipped for continuous inflow and removal of water, and the retention time of water in the column can be varied from 20 to 180 days. The movement of various chemical constituents into or out of the water column relative to the underlying soil is assessed by monitoring changes of the chemical constituent with time in the water column.

(1) Applicability. The soil-water reaction chamber is used to evaluate oxygen depletion rates and rates of release of nutrients and metals in water overlying newly flooded soils from proposed impoundment areas or in water overlying sediments from established reservoirs. The retention time of water in the water column can be adjusted to be comparable to that expected for the actual reservoir. The duration of the test can be varied to assess the changes in water quality resulting from various lengths of reservoir aging. The incubation temperature, variable from 5° to 35° C, can be set to include one or several of the temperatures anticipated in the reservoir over a yearly cycle. The soils tested in the chamber can be selected to represent one or several major soil types present in the central reservoir basin or tributaries.

(2) Implementation and interpretation. Methods for conducting soil-water reaction studies have been developed (Ref. 70). Detailed interpretation of oxygen consumption by flooded soils and sediments has been described by Gunnison et al. (Ref. 71). Use of soil-water reaction chambers to predict releases of nutrients and metals in new reservoirs has also been considered. The data obtained from these studies may be used for direct assessment of corrective strategies to be applied during reservoir site preparation (Refs. 14 and 15). Alternatively, data obtained from these studies may be compared with data obtained from other sources, i.e., other lakes and reservoirs in the impoundment area, or the data may be used to generate rate coefficients for use in mathematical water quality models.

4-9. Statistical Techniques. Statistical methods represent a broad spectrum of analytical and predictive techniques. These methods generally have rigorous data requirements for development and testing and involve numerous conditions and assumptions that must be satisfied if the model and its applications are to be valid. Box et al. (Ref. 53) provide general guidance on the philosophy and use of empirical methods. Specific predictive techniques include regression analysis (Ref. 99) and time series analysis (Refs. 54 and 95). A variety of computer programs are available to assist in model development and use (e.g., SAS Institute) (Ref. 96).

a. Applicability. Statistical techniques can be used to model systems or relationships in which the underlying mechanisms are not understood or are stochastic in nature, provided the important variables have been identified and monitored and that the underlying cause-effect relationships are stable. Examples include the modeling and forecasting of hydrologic or meteorologic time series and the generation of water quality data from a surrogate variable (e.g., using specific conductance data to generate total dissolved solids values). Statistical methods also provide estimates of prediction error. Most statistical models employ relatively rigorous assumptions regarding the characteristics of model residuals (observed minus predicted responses), randomness, normality, and variance stability. Use of a statistical model also assumes that the relationship is stable in time. If changes occur in implicit factors that could influence the relationship, the model should be tested and, is necessary, reconstructed.

b. Implementation and Interpretation. Steps in the development of a statistical (empirical) model include data compilation, preliminary analysis, model formulation, calibration, and testing. Model development is usually an iterative process that requires statistical expertise and familiarity with the system being modeled. Underlying assumptions and limitations should be considered in interpreting the predictions of statistical models. Prediction errors can be estimated and used in model applications. In some cases, empirical model development can lead to an improved understanding of the system and its controlling variables and to formulations of mechanistic models.

4-10. Water Quality Indices. Water quality indices are summary statistics usually composed of multiple variables combined into a single measurement. There is a loss of information on any summarization; however, the convenience involved in the use of smaller data sets can be advantageous. The attribute which the index is attempting to relate dictates which variables comprise the particular index. A more detailed discussion of indices is provided in Reckhow and Chapra (Ref. 94). Water quality indices have been used since the 19th century to indicate the quality of drinking water. These early indices used biological components, while more recent indices use more quantitative chemical components. Limitation in the use of indices stems from the loss of information and extensive summarization. Further, there is disagreement among experts on the interpretation of indices.

4-11. Remote Sensing. Remote sensing techniques include the use of aerial imagery and satellite or aircraft-borne multispectral scanners to qualitatively and/or quantitatively describe reservoir water quality constituents. Differences in energy levels due to water color, turbidity, temperature, etc., are detected by the camera or sensor. Variations in the energy levels of different wavelength bands (i.e., spectral signatures) may be correlated with varying constituent concentrations in the water. Quantitative remote sensing is usually accomplished through computer enhancement and analysis of the spectral data. Remote sensing is discussed in detail in EP 70-1-1.

a. Applicability. Aerial overflights and satellite imagery (e.g., Landsat-4) can provide relatively thorough coverage of surface water quality characteristics within a reservoir. Constituents that influence spectral patterns, such as chlorophyll, dissolved oxygen, temperature, and turbidity, can be measured. Changes in the distribution of shoreline vegetation, aquatic macrophytes, and delta sediment deposition can be monitored. Satellites and medium-altitude aircraft permit the entire reservoir surface area to be viewed instantaneously, allowing areal gradients in constituent concentrations to be observed. The underlying assumption in remote sensing is that materials that have the same spectral signatures are alike. For example, when a computer-enhanced image is produced, it is assumed that areas of the image with similar intensities represent similar concentrations of a specific parameter (e.g., chlorophyll). Satellite imagery in general is limited in spatial resolution and coverage. For sun-synchronous satellites such as Landsat-4, coverage is only periodic. Medium-altitude aircraft imagery also has limited spatial resolution and can be expensive to obtain, thereby limiting the amount of imagery that can be collected. Use of light aircraft to obtain areal imagery allows better spatial resolution but is limiting in the extent of coverage. A large reservoir, therefore, cannot be imaged simultaneously but must be imaged in segments. Remote sensing requires ground truthing, good optical conditions (i.e., sun angles, temperature, and lack of particulate material and water vapors in the atmosphere), and special technical expertise for imagery interpretation.

b. Implementation and Interpretation. Remote sensing data are interpreted either visually from photographs or with the aid of a computer. There is, however, a minimum spatial resolution. A priori knowledge (i.e., ground truth information) is usually required to determine the desired information. The resulting spatial variations can be used to infer morphometric characteristics and patterns of circulation, warming, and growth. A time series of images can be used to show changes in spatial characteristics.

Section III. Predictive Techniques

4-12. General. Predictive techniques are assessment methodologies that can be used to predict the quality conditions in a proposed reservoir and its releases, and the effect of specific management or operational alternatives on the reservoir and release water quality at an existing project.

4-13. Regression Analysis.

a. Regression analysis is a statistical technique that can be used for analyzing data as well as for some limited modeling. (Such an exercise must be conducted with caution due to the absence of deterministic laws.) The basis of regression analysis is examination of the relationship between two or more variables (multiple regression). An example is the relationship between conductivity and dissolved solids. Correlation between these two variables is positive, and if a regression model is developed, one variable may be used to predict the other variable. Multiple regression involves numerous variables used to predict one variable.

b. Analyses of this type are applicable to most water quality variables in which the population is assumed to be normal. The variables used to predict the unknown variable are also assumed to be independent, although in many cases they may not be. The range of the prediction is limited by the extremes in the original data set, as the variance outside this range is unknown.

4-14. Comparative Analysis.

a. Surrounding water bodies that include not only other reservoirs but also lakes, streams, and rivers in the same geographic area may be used for comparative analysis.

b. Surrounding water bodies may provide information valuable to an understanding of existing water quality problems, generality or specificity of these problems, or potential solutions. Surrounding water bodies may be the major source of information on stratification, nutrient levels and cycling, other water chemistry components, biological species composition, diversity and problem species, and release water quality. Data from surrounding water bodies can also be used to make projections of the water quality of proposed reservoirs and the effects of implementing management alternatives for existing reservoirs. Specifically:

(1) Reservoirs in the same geographic area will have similar macrometeorology, geology, and land use and, therefore, may indicate generic and species water quality conditions.

(2) Land use changes in other watersheds may provide an indication of future conditions or concerns.

(3) Assessment strategies used in surrounding water bodies may indicate the effectiveness of these strategies.

(4) The influence of morphometry, hydrology, meteorology, and reservoir operation may be assumed from surrounding water bodies and used to project water quality conditions for proposed reservoirs.

(5) Surrounding water bodies are assumed to respond to external and internal factors similar to the reservoir under study. If surrounding water bodies are used as a basis for predicting future water quality conditions for the prototype, it is assumed the prototype will respond in a similar manner. Conclusions and recommendations on water quality are predicated on the design and objectives of the sampling program. These sampling objectives may limit the transfer of conclusions to the prototype reservoir if study objectives are different. A study addressing phytoplankton, for example, may have limited data relating to high manganese concentrations in the releases.

4-15. Modeling.

a. All models are, by definition, representations of actual processes. One of the benefits of this representation is that the model can be manipulated for less cost and in a shorter time than experimentation on the prototype. One of the costs associated with this benefit is that assumptions are used to simplify the real system, and these assumptions can impose limitations on the use and interpretation of model results. Therefore, one must be familiar with model assumptions before selecting and implementing a model.

b. The following steps are generally involved in the use of models.

(1) Model selection. An appropriate model or set of models should be selected for application to a given problem, based upon the assessment objectives, water body characteristics, available data, model characteristics, literature guidance, and regional experience. Uncertainty in the selection of alternative models can be addressed by applying more than one model simultaneously.

(2) Data compilation. Most of the effort involved in implementing a model is directed toward gathering and processing input data. The data required will vary depending upon the assessment to be made and the model selected. Data categories include tributary hydrology and nutrient concentrations; impoundment morphometry, hydrology, and water quality conditions; reservoir and outlet structure characteristics; and numerous physical, biological, and chemical coefficients.

(3) Calibration/verification. All models require calibration with existing data. Calibration procedures should include water budget, hydraulic transport, and all model constituents. Whenever possible, the calibrated model should be applied to an independent data set to verify the calibration.

(4) Application. After the model is calibrated, it can be used to investigate various operational and management alternatives. Care should be used in applying the model outside the range of conditions used in the calibration/ verification simulations. Sensitivity and error analysis should be part of all applications. When interpreting model results, consideration must also be given to all model assumptions concerning spatial discretization, solution technique, density stratified flow, and constituent formulations. Model results must also be explainable and realistic.

c. Detailed discussions of the use of nutrient loading models, numerical simulation models, and physical models for reservoir water quality assessment are presented in paras 4-16 through 4-18.

4-16. Nutrient Loading Models. Nutrient loading models are simplified techniques that predict spatially and temporally averaged water quality conditions related to eutrophication, including nutrients, algal growth, organics, transparency, and hypolimnetic DO depletion. Input variables include morphometric, hydrologic, and nutrient inflow characteristics averaged on an annual or seasonal basis. Typical control pathways are shown in Figure 4-2. The models are based upon the average mass balance of the growth-limiting nutrient (usually phosphorus) for an impoundment. The Organization for Economic Cooperation and Development has summarized information on loading model structures, applicability, and limitations as applied both to lakes and reservoirs (Ref. 93). Walker discusses reservoir nutrient loading models (Refs. 28 and 29).

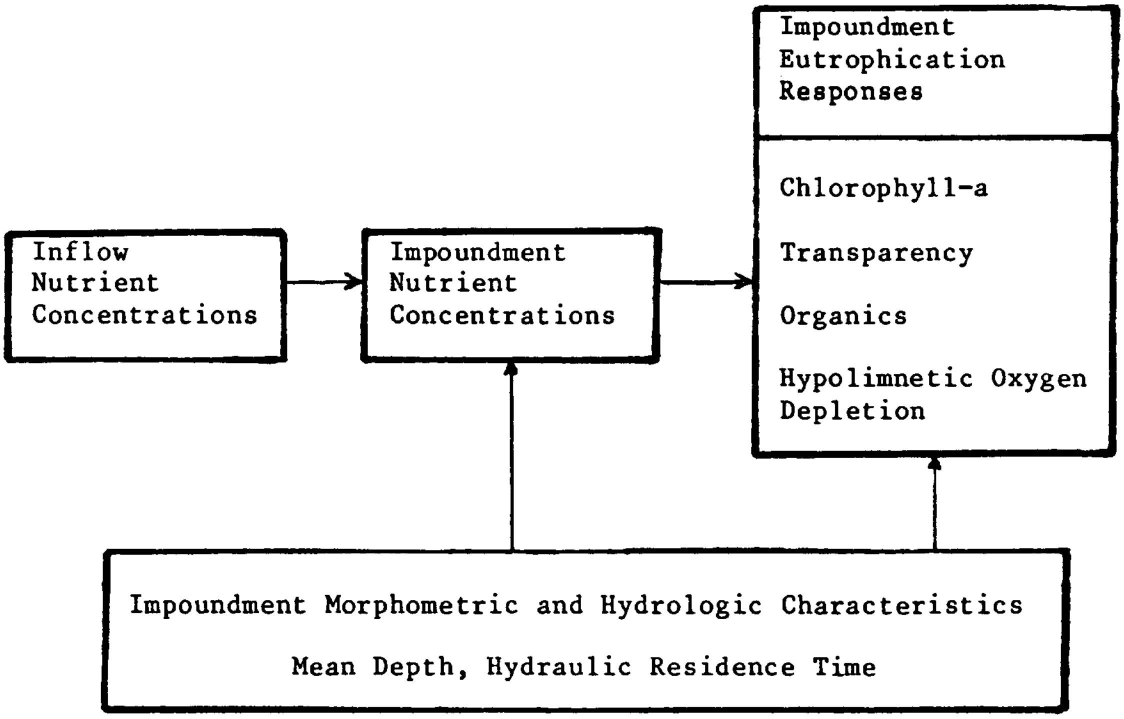


Figure 4-2. Control pathways in a typical nutrient loading model

a. Applicability. Because of their simplicity, low data requirements, low calibration requirements, and error analysis, nutrient loading models are especially useful for preliminary analyses, screening, and problem identification. They can provide a portion of the information needed to decide whether more detailed simulation modeling of a given problem is warranted. Specific applications include:

(1) Assessments of trophic status and controlling factors in a given impoundment.

(2) Comparisons or rankings of trophic status within a given group of impoundments, typically on a regional basis.

(3) Predictions of long-term-average water quality changes and resulting changes in average nutrient loading, morphometry, and/or hydrology.

(4) Prediction of the trophic status of a new reservoir.

b. Assumptions. Typical assumptions inherent in nutrient loading formulations are as follows:

(1) Loading models assume the impoundment to be well mixed (i.e., treated as a continuous stirred reactor).

(2) Most loading models assume that average impoundment nutrient balances and water quality conditions are at steady state.

(3) Most loading models assume that algal populations and other eutrophication-related water quality variables change in direct response to total phosphorus concentration. Potential effects of other limiting factors, such as nitrogen, light, nutrient bioavailability (dissolved versus particulate), and/or flushing, are not directly considered.

(4) Nutrient mass balances are formulated by considering external sources (e.g. tributaries, direct point and nonpoint sources, and atmospheric loading) in relation to discharge through the reservoir outlet. Although different model formulations employ different assumptions to estimate net nutrient sedimentation from the water column, most models assume that internal nutrient loadings generated from bottom sediments are insignificant.

c. Limitations. Important limitations of nutrient loading models include:

(1) Empirical models should not be used on impoundments that do not conform to the limits of the data set used to develop and calibrate the model.

(2) Loading models cannot be used for detailed evaluation of effects of impoundment design or operational characteristics.

(3) Loading models are generally designed to predict spatially and temporally averaged conditions. Increased spatial resolution can be achieved by plug flow models and numerical models.

(4) Standard errors of models calibrated to Corps impoundments range from 15 to 50 percent for various response variables.

d. Model Testing. A variety of loading models have been systematically calibrated and tested for use in Corps impoundments (Ref. 28). If the difference between observed and predicted conditions is outside the expected confidence range when all sources of error have been considered, the reservoir should be considered atypical of the impoundments used to develop the model, and an alternative loading or simulation model should be investigated. Recalibration of certain parameters to data from a specific impoundment reduces prediction error and may be appropriate in some cases.

e. Model Application. Year-to-year variability in loadings and water quality conditions should be assessed, based upon long-term monitoring data. Potential errors in the estimates of model input and output variables resulting from use of limited monitoring data should be calculated to provide a basis for assessing data adequacy. For applications to an existing reservoir, model applicability can be tested by comparing observed and predicted water quality conditions.

4-17. Numerical Simulation Models. Numerical simulation models are computer programs designed to reproduce the water quality responses of a reservoir and its associated stream system to external flow, loads, and energy inputs and to internal processes. Simulation models represent one of the most common and useful techniques available for analyzing and predicting reservoir water quality. Simulation models generally have two modules, a flow simulation module and a water quality module. Use of a simulation model requires that the water body be idealized into series of discrete control volumes or an appropriate grid system. For each control volume or grid point, the conservation equations are solved along with the water quality kinetic equations. Several different techniques are used to solve the equations in different models, while the method used for system discretization must conform to the equation solution methodology.

a. Classification. Simulation models are classified according to spatial dimensions, time derivative (dynamic or steady state), and water quality constituents simulated by the model.

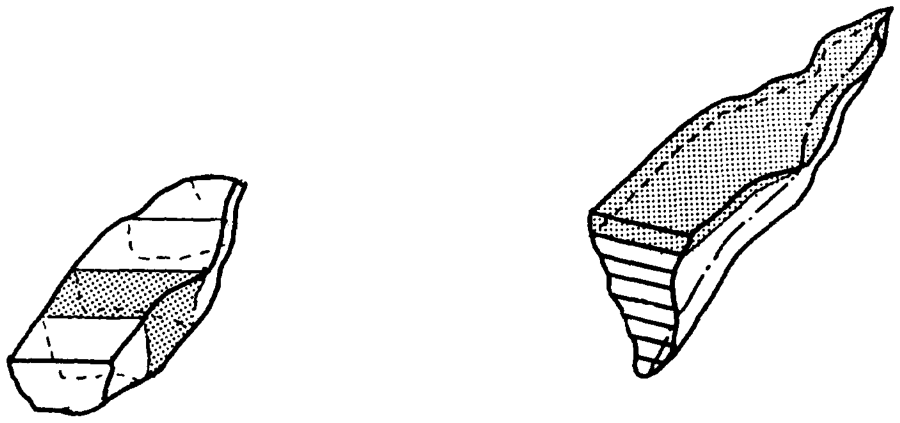
(1) Spatial. Simulation models are classified as one-, two-, or three-dimensional models, depending upon the number of dimensions along which gradients are simulated (Figure 4-3). In general, the spatial dimensionality of the flow simulation and the water quality modules are the same.

(a) One-dimensional models simulate flow and water constituent concentrations in the direction of one principal gradient (e.g., the direction of flow for streams and the vertical axis (depth) for deep reservoirs).

(b) Two-dimensional models simulate gradients along any two of the three coordinate axes. A horizontal plane, two-dimensional model simulates gradients along the length and width of a water body but assumes the water body is vertically homogeneous. The vertical plane, two-dimensional models simulate gradients along the length and depth of a water body since the water body is assumed to be laterally homogeneous. A third type of vertical plane, two-dimensional model exists that simulates gradients laterally across a water body with depth, but the applicability of this type model to reservoir water quality engineering is limited.

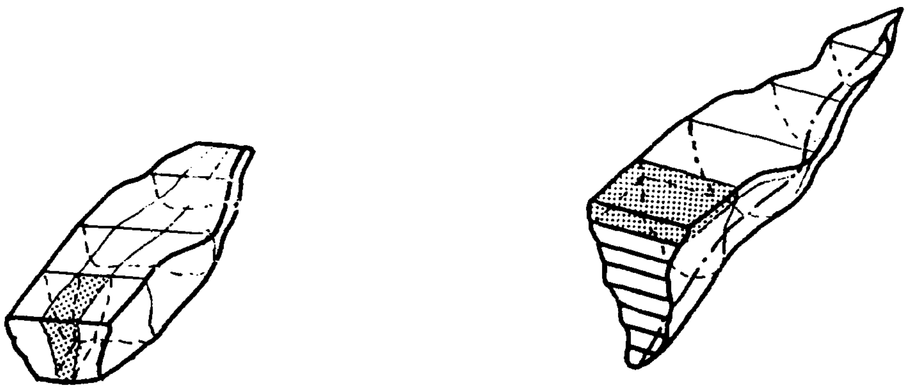
(c) Three-dimensional models provide the closest approximation to reality by simulating gradients along all of the three coordinate axes: along the longitude of the water body, laterally across the water body, and with depth (Refs. 16 and 35). Currently, three-dimensional reservoir water quality models are research models only and are not available for general use.

(2) Temporal. Models are classified as steady state or dynamic depending upon the treatment of the time derivative in the governing equations by



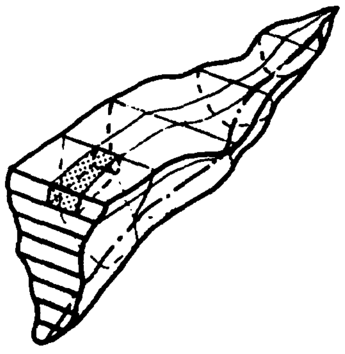
A. ONE-DIMENSIONAL HORIZONTAL

B. ONE-DIMENSIONAL VERTICAL



C. TWO-DIMENSIONAL HORIZONTAL

D. TWO-DIMENSIONAL VERTICAL



E. THREE-DIMENSIONAL

Figure 4-3. Comparison of model dimensions the solution technique. If the time derivative is set equal to zero, the model is steady state. Results obtained from a steady-state model are interpreted as conditions that would be expected if the given input conditions were to prevail for an indefinite period of time. If the time derivative is not set equal to zero, it becomes part of the solution procedure and the model is dynamic and computes time-varying results. Both the flow simulation and water quality/ecological simulation modules can either be steady state or dynamic. Compatible temporal characteristics must be maintained between modules. If both modules are either steady state or dynamic, compatibility is maintained absolutely. However, use of a dynamic flow simulation module with a steady-state water quality/ecological simulation module must be done with care to maintain compatibility and to ensure that realistic results are obtained.

(3) Constituents. Water quality/ecological simulation models are further classified according to the number and types of constituents that are simulated by the model. The simplest water quality simulation models perform simulations for one or more conservative constituents (those constituents that do not react or decay and the concentration of which is changed only by dilution and dispersion). More common are water quality simulation models that simulate temperature and the DO cycle (i.e., carbonaceous biochemical oxygen demand, nitrogeneous oxygen demand). A reservoir water quality model flowchart (CE-QUAL-R1) (Ref. 10) including constituents and pathways is shown in Figure 4-4. In general, the more extensive the list of constituents simulated, the more comprehensive the database must be to support the model, its calibration, and verification.

b. Available Models. The selection of the appropriate model for a reservoir water quality assessment should be based on a comprehensive understanding of the need for the assessment, the decisions that must be made, the relationship of the model results to the decision-making process, and the degree of detail in modeling that is required to obtain results for decision-making. Thus, the spatial, temporal, and constituent characteristics should be considered simultaneously in selecting a model to be used for analysis. However, spatial considerations are commonly used as an initial step in screening available models. For this reason, several available and tested models are reviewed below for applicability to reservoir water quality studies on the basis of spatial characteristics (Table 4-2). The list is not exhaustive, and other models, not contained in the review, can be used for the appropriate analyses. A number of reviews of existing water quality models are available (Refs. 18, 30, 35, and 51).

(1) One-dimensional horizontal.

(a) Description. One-dimensional horizontal models simulate flow and water quality/ecological constituent concentrations in the direction of flow, which is usually along the longitudinal axis of a reservoir or stream (Figure 4-3a). Existing models that have been used by the Corps include the dynamic flow riverine water quality model developed by Bedford et al.

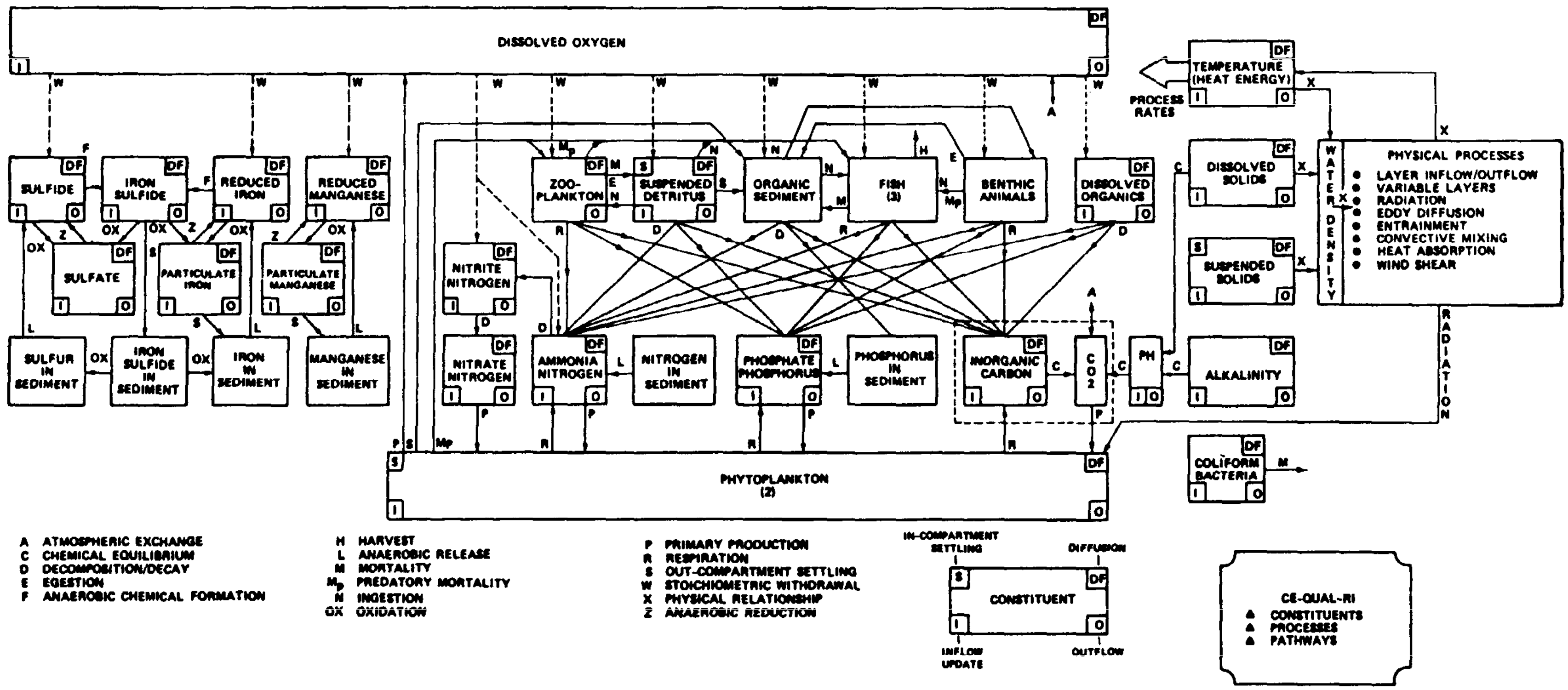


Figure 4-4. Typical water quality model constituents and pathways (from CE-QUAL-R1, Ref. 10)

TABLE 4-2

Summary of Simulation Model Attributes

	ONE-DIMENSIONAL HORIZONTAL		ONE-DIMENSIONAL VERTICAL		TWO-DIMENSIONAL HORIZONTAL		TWO-DIMENSIONAL VERTICAL	
	STEADY STATE	DYNAMIC	THERMAL	WATER QUALITY	HYDRODYNAMIC	WATER QUALITY	HYDRODYNAMIC	WATER QUALITY
USER DOCUMENTATION	G	G	G	G	F	P	F	P
MODEL TYPE								
DETERMINISTIC	●	●	●	●	●	●	●	●
STOCHASTIC	—	—	—	●	—	—	—	—
TRACK RECORD	G	G	G	G	G	F	G	F
APPLICABLE WATER BODY								
RIVERS	●	●	—	—	●	●	—	—
WIDE RIVERS	—	—	—	—	●	●	—	—
SHALLOW RESERVOIRS	●	●	—	—	●	●	—	—
DEEP RESERVOIRS	—	—	●	●	—	—	●	●
PHYSICAL PROCESSES								
TEMPERATURE	●	●	●	●	●	●	●	●
TDS	●	●	●	●	●	●	●	●
SUSPENDED SOLIDS	●	●	●	●	●	●	●	●
ICE	—	—	●	●	—	—	●	●
RESERVOIR REGULATION								
SELECTIVE WITHDRAWAL	—	—	●	●	—	—	●	●
WEIR FLOW	—	—	●	●	—	—	●	●
HYDROPOWER, PUMP STORAGE	—	—	●	●	—	—	●	●
DOWNSTREAM OBJECTIVE	—	—	●	●	—	—	—	—
OPTIMIZATION	—	—	●	—	—	—	—	—
CHEMICAL								
DISSOLVED OXYGEN	●	●	—	●	—	●	—	●
ORGANIC CARBON (BOD)	●	●	—	●	—	●	—	●
PH-CARBONATE EQUILIBRIUM	●	●	—	●	—	—	—	●
PHOSPHORUS	●	●	—	●	—	●	—	●
NITROGEN SERIES	●	●	—	●	—	●	—	●
SILICA	—	—	—	●	—	—	—	—

TABLE 4-2 (Concluded)

	ONE-DIMENSIONAL HORIZONTAL		ONE-DIMENSIONAL VERTICAL		TWO-DIMENSIONAL HORIZONTAL		TWO-DIMENSIONAL VERTICAL	
	STEADY STATE	DYNAMIC	THERMAL	WATER QUALITY	HYDRODYNAMIC	WATER QUALITY	HYDRODYNAMIC	WATER QUALITY
BIOLOGICAL								
ALGAE	●	●	–	●	–	–	–	●
DETRITUS	●	●	–	●	–	–	–	●
HIGHER ORDER	●	●	–	●	–	–	–	–
COLIFORMS	●	●	–	●	–	●	–	●
RECOMMENDED APPLICATIONS								
INFLOW QUALITY	●	●	–	–	–	–	–	–
INLAKE PREDICTIONS								
THERMAL STRATIFICATION	–	–	●	●	–	–	●	●
DO DYNAMICS	●	●	–	●	–	●	–	●
ALGAE	●	●	–	●	–	–	–	●
RELEASE QUALITY								
TEMPERATURE	●	●	●	●	–	–	●	●
DO	●	●	–	●	–	–	–	●
ORGANICS	●	●	–	●	–	–	–	●
METALS	–	–	–	●	–	–	–	–
DOWNSTREAM PREDICTIONS								
TEMPERATURE	●	●	–	–	●	●	–	–
DO	●	●	–	–	–	●	–	–
ORGANICS	●	●	–	–	–	●	–	–
METALS	●	●	–	–	–	–	–	–

G - GOOD
F - FAIR
P - POOR

(Ref. 52) (referred to as CE-QUAL-RIV1), the Water-Quality for River-Reservoir Systems (WQRRS) river module of the US Army Engineer Hydrologic Engineering Center (Ref. 38), QUAL-II (Ref. 36), and the MIT Transient Water Quality Network Model (Ref. 31). Several of these models have been reviewed by McCutcheon (Ref. 18).

(b) Applicability. One-dimensional horizontal models can be used to route flow and associated constituents into a reservoir from an upstream sampling station and to route reservoir releases and the associated constituents downstream. Small, shallow, well-mixed, main-stem reservoirs and reregulation pools can also be simulated using one-dimensional horizontal models. Since most of these models were originally developed for wasteload allocation studies, the models may not have all of the necessary constituents for reservoir water quality studies. One-dimensional horizontal models have minimal data requirements and are usually well documented. Since the models have been extensively used, most internal coding errors have been corrected. One-dimensional horizontal models assume the principal gradient is in the direction of flow or along the longitudinal axis. Gradients lateral to the flow, across the stream and with depth, are assumed not to exist. The models typically assume conservation of mass for each constituent, including water (Figure 4-5). Every model makes specific assumptions concerning geometric features, hydraulic transport, and constituent formulations. These assumptions are usually given, although not always explicitly stated, in the user documentation. Results computed using one-dimensional horizontal models are interpreted as being an average across the stream or reservoir cross section at the point of computation. If the model is steady state, the results are interpreted as the average over the travel time for the entire system. A dynamic flow model should be used for streams and/or pools that receive

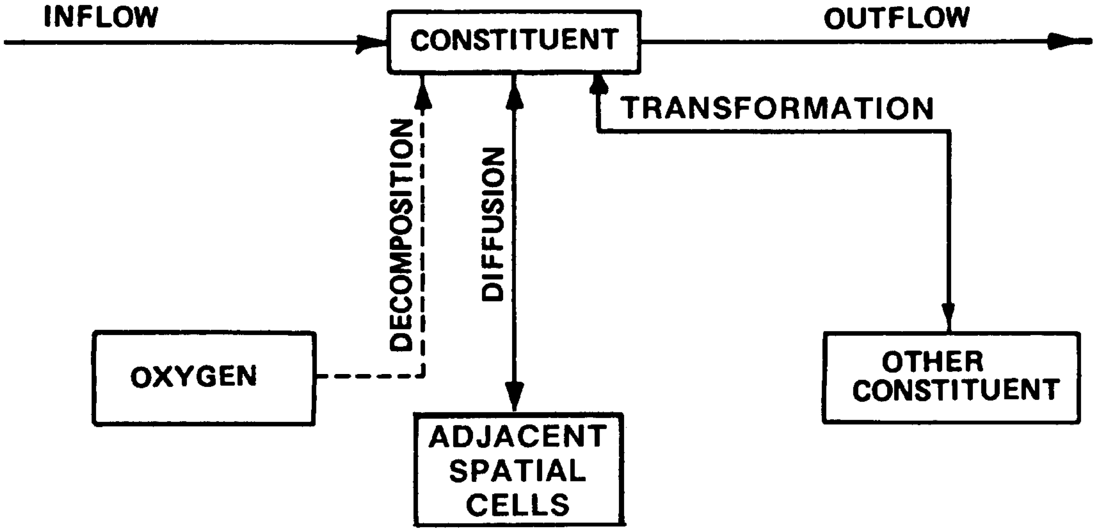


Figure 4-5. Model representation for conservation of mass

unsteady flows, such as tailwaters and/or reregulation pools below peaking hydropower projects.

(2) One-dimensional vertical.

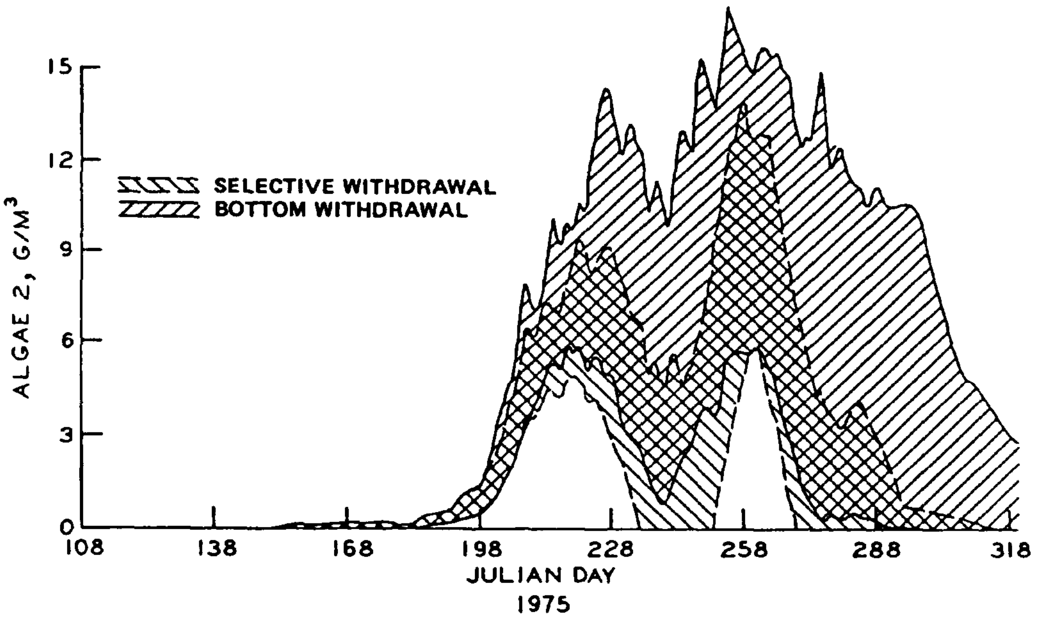
(a) Description. One-dimensional vertical reservoir or lake models consider the water body to be represented by a vertical series of well-mixed horizontal layers (Figure 4-3b). The models usually simulate the time-varying vertical distribution of constituents. The number and type of constituents considered by specific models vary from temperature only to complete water quality models that consider higher trophic levels through fish. These models typically are unsteady and use a time step of a day.

(b) Applicability. One-dimensional vertical models are usually applied to large, deep reservoirs with long residence times where the effects of thermal stratification are significant. At a minimum, these reservoirs should have surface areas greater than 1 square kilometer, maximum depths greater than 10 meters, and mean annual residence times greater than 20 to 30 days. (Item k, Appendix B, provides more detailed information.) One-dimensional vertical reservoir models have also been shown to accurately predict changes in reservoir water quality due to changes in project operation and management. The models are logically structured, well tested, and inexpensive to use.

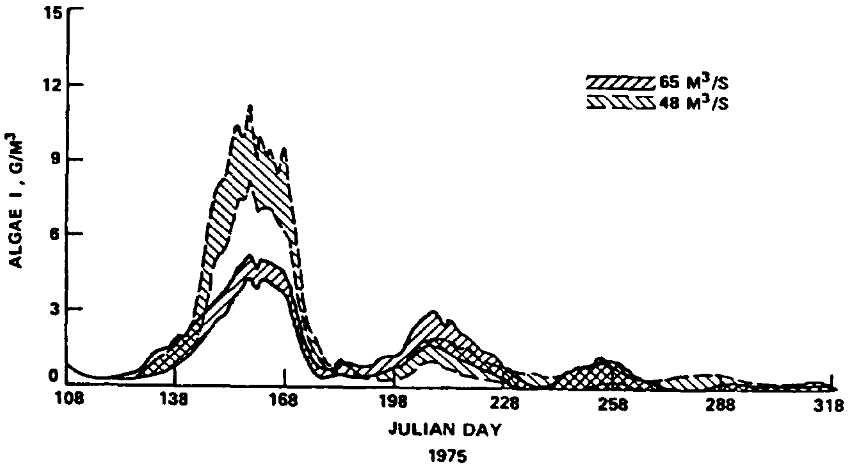
(c) Specific problems addressed. One-dimensional vertical models such as CE-QUAL-R1 (Ref. 10) can be used to address the following: seasonal variations in thermal stratification and DO, including the development of anoxic conditions; effect of structural modifications (i.e., selective withdrawal) and operational changes (e.g., guide curve) on water quality (see Figure 4-6 for example); magnitude, composition, and timing of algal blooms and factors limiting algal growth; effects of storm events and upstream land use on inpool and release water quality; and release from sediments into the water column of reduced species under anoxic conditions.

(d) Limitations. One-dimensional vertical models assume a reservoir can be represented by a vertical series of well-mixed horizontal layers. The equations for each constituent are usually based on conservation of mass. Since the models cannot predict longitudinal variations, they should not be used to address headwater problems or to simulate small, shallow impoundments that do not stratify and are dominated by advection. Model results are interpreted as being an average across a horizontal plane through the reservoir and are probably most representative of the region near the dam. Because of the aggregation of biological species into a few parameters, the models can predict only general trends, not competition between species nor precise numbers of species. In general, the kinetic formulations are simple zero- or first-order reactions, and the number of biological species is severely limited.

(3) Two-dimensional horizontal.



a. Structural modification



b. Operational modification

Figure 4-6. Statistical comparison of computer simulation results for two management alternatives

(a) Description. Two-dimensional horizontal models simulate gradients along the length and width of a water body but do not simulate gradients that exist with depth (Figure 4-3c). A number of different approaches have been used to spatially discretize the water body. These include stream tubes (Ref. 102), finite difference formulations, finite element formulations (Ref. 92), and boundary fitted coordinates (Ref. 23). In general, the models simulate flow and a limited number of constituents such as temperature, dissolved solids, suspended solids, BOD, and DO.

(b) Applicability. Two-dimensional horizontal models are generally used to simulate flow patterns in large, wide rivers and in shallow, wide reservoirs that are vertically well mixed (i.e., not stratified). The models have been used to investigate sediment transport, thermal plumes, and the movement, dispersion, and decay of simple constituents. Two-dimensional horizontal models can provide an accurate representation of complex flow patterns in systems that are characterized by complicated morphometry. Each model has specific assumptions concerning spatial discretization, hydrodynamics, and constituent formulations.

(c) Limitations. The major limitations of two-dimensional horizontal models are: since they are, in general, complicated, they require an experienced modeler; for reservoirs, they have received minimal use and are therefore not tested; they have a limited number of constituents; and they require considerable computation time.

(4) Two-dimensional vertical.

(a) Description. Two-dimensional vertical models simulate flow patterns and gradients in temperature and other model constituents with length and depth (Figure 4-3d). The models that have received the most use in the Corps are LARM (Ref. 8), CE-QUAL-W2 (User Manual) (which is LARM with water quality added), and RMA-7 (Ref. 33).

(b) Applicability. Two-dimensional vertical models are usually used to simulate variations in flow patterns and temperature stratification in large, narrow, deep reservoirs at both a seasonal time scale and for shorter time periods to investigate specific events. The models can be used to describe the movement of inflowing constituents through reservoirs (Ref. 82) and to predict vertical and longitudinal gradients in water quality. These models provide valuable information on density-stratified flow patterns, inflow density currents, and longitudinal variations in constituents. The CE-QUAL-W2 model is the LARM model with specific water quality constituents added. LARM and CE-QUAL-W2 have the capability to model reservoirs having more than one main tributary.

(c) Limitations. Two-dimensional vertical models assume the water body is well mixed laterally. In addition, each model has specific assumptions concerning spatial discretization, branching, hydrodynamics, and constituent formulations and require considerable computation time. Special attention must be given to assumptions that impact density and flow computations. Further, two-dimensional vertical models are limited in the number of constituents simulated. Since some Corps reservoirs are dendritic and may not be laterally well mixed, it may be necessary to use branching features to model embayments.

(5) Basin models.

(a) Description. Basin models are advantageous in that a single model can be used to analyze both stream and reservoir water quality. Basin models used by the Corps include WQRRS (Ref. 38) and HEC-5Q (Ref. 37). The WQRRS consists of three separate modules called the reservoir module, the stream hydraulic module, and the stream water quality module. Each module is a stand-alone program that may be executed, analyzed, and interpreted independently, or the modules can be integrated into a complete basin model. The HEC-5Q is an integrated stream-reservoir flow and water quality simulation model that was developed to assist in studies for evaluating proposed or existing reservoirs in a system for reservoir flow control and water quality requirements recommended for the system. The HEC-5Q consists of a flow simulation module and a water quality module. The flow simulation module can be executed as a stand-alone model, or the flow simulation and water quality modules can be executed as a single integrated model. However, the water quality module cannot be executed as a stand-alone model.

(b) Applicability. Both models are applicable to a variety of basin water quality engineering analyses and will simulate a limited list of water quality and ecological constituents. The WQRRS can be executed with a variety of flow-routing options, including steady state and dynamic routing, so that riverine systems with a wide variety of flow characteristics can be simulated. The HEC-5Q is applicable to river basin analyses for up to 10 reservoirs in an arbitrary configuration and for up to 30 control points. Reservoir operation strategies required to meet system flow, water quality, and hydropower objectives are developed within the model. Consequently, reservoir discharges do not have to be developed before the program is run. An economic evaluation package is also available to compute expected annual flood damages, system costs, and net benefits for flood damage reduction, including both structural and nonstructural alternatives.

(c) Limitations. In general, basin models are one dimensional and are limited in the number of constituents. The stream hydraulic and water quality modules are usually one dimensional along the longitude of the stream while the reservoir modules are usually one dimensional along the vertical axis of the reservoir. Water quality kinetics in basin models are usually simplified and assumed to be aerobic. Because HEC-5Q is very comprehensive, the time and expense of applying it may not be justified for studies that do not focus on several project purposes in addition to water quality.

c. Implementation. Numerical simulation models for water quality involve physical, chemical, and biological processes that are coupled through the solution of partial differential equations. Usually a simulation model must be modified or adapted for site-specific characteristics. Therefore, an application can require the interaction of specialists in the areas of hydraulics, chemistry, biology, and numerical methods. The WES and the HEC maintain a staff of specialists that can be consulted on these types of studies or can assist with the application. Application of most numerical models generally requires a manpower effort on the order of months. Computer costs depend on the model (e.g., dimensionality), the spatial and temporal scale, the simulation scenarios, and the computer used for the study. The CPU time for computer model simulations has ranged from seconds to hours.

4-18. Physical Models. Physical models have proven to be valuable tools in understanding complicated three-dimensional flow patterns and boundary conditions and in designing hydraulic structures. In this section, physical model studies are considered, including both generalized laboratory studies of specific physical mixing and flow processes and scaled representations of prototype systems. Additional information on physical modeling techniques can be found in Ref. 49.

a. Generalized Models.

(1) Description. Generalized models are laboratory model studies performed in existing laboratory flumes or tanks to investigate the parametric relationships of specific circulation and mixing processes. The laboratory flumes or tanks are selected to minimize geometric and boundary effects. The specific physical process under investigation must be scaled properly to achieve useful results. The laboratory studies are usually performed over a wide range of conditions (i.e., varying flow rates, densities, stratification), and empirical relationships are developed using governing parameters determined by dimensional analysis and similitude arguments.

(2) Applicability. Results from the generalized model studies can be used for simplified calculations or to form the basis for specific algorithms in complex simulation models. Examples of generalized laboratory studies that are important for water quality studies include:

(a) Formulations for the thickness of withdrawal zones based on flow rate, density stratification, and outlet geometry. (Different formulations are available for small portals, large portals, free weirs, and submerged weirs.)

(b) Formulations for the plunge point location, inflow density, current, thickness and speed, and entrainment rates based on inflow density, flow rates, and ambient reservoir stratification.

(c) Entrainment rates into pumpback jets based on flow rates, jet density, jet location and geometry, and ambient reservoir stratification.

(d) Aeration rates for various types of outlet structures.

(e) Design guidance on sizing hydraulic destratification systems.

(f) Other studies such as sizing constrictions in bridges and causeways.

(3) Discussion. In addition to developing empirical relationships that have general applicability, generalized laboratory studies also provide valuable insight into the specific process through visual observations. It is assumed that the process being simulated in the laboratory functions similarly to the actual process in the prototype in terms of both forcing and response. Scaling criteria such as the Froude number and densimetric Froude number are used to determine the similarity. The specific scaling criteria will, however, depend on the experiment. The model studies are normally limited to one specific process and, therefore, do not include synergistic effects with other mixing and circulation processes that occur in natural systems.

b. Prototype Models.

(1) Description. Prototype models are physical representations of prototype systems, but at a much smaller spatial scale. It is assumed that if the models are properly scaled, the flow patterns observed in the model should be similar to the flow patterns occurring in the prototype. An introduction to scaling and similitude is given in Ref. 74. Prototype models are called "undistorted" if the vertical and horizontal dimensions are equally scaled and "distorted" models if the vertical and horizontal dimensions are scaled differently.

(2) Undistorted models. Undistorted physical models are scaled reproductions of a prototype system including site-specific topography, outlet geometry, and operation schemes. Since the horizontal and vertical dimensions are equally scaled, it is usually infeasible to reproduce the entire prototype, and the extent or coverage of the model is usually limited to a small area of interest (e.g., the area near the outlet structure). Therefore, undistorted models usually are used to investigate near-field effects.

(a) Application. Undistorted models can be used to investigate the effects of complex topography, unique inlet-outlet geometry (e.g., approach channels, side ports, etc.), generation and pumpback discharge rates, ambient stratification and operating conditions on withdrawal zones, inflow zones, and pumpback jets. Information from these studies on circulation patterns and entrainment rates can be used to modify designs to improve water quality and as input to simulation models for site-specific characteristics. The use of undistorted models offers two major advantages: first, the ability to reproduce complex, three-dimensional flow patterns; second, the ability to actually observe the flow patterns.

(b) Limitations. Most undistorted models are based on Froudian scaling, which means the inertial and gravitational forces are similar in both the model and the prototype. When density differences are important, the densimetric Froude number must also be similar in both systems. The effects of other forces (e.g., viscous forces) are assumed to be negligible. The results from undistorted models are limited to the spatial extent of the model and to the conditions under which the model was operated. These conditions include flow rates, operating schemes, and type and strength of density stratification. In addition, most models do not include energy exchanges at the air/water interface due to wind and meteorological effects. Synergistic effects between these energy sources and the flow fields are not included.

(3) Distorted models. In many natural systems, the disparity between the vertical and horizontal dimensions is sometimes so great (i.e., 1 to 1,000) that it is not feasible to construct a model of the entire system with equal horizontal and vertical scales. The horizontal scale is, therefore, compressed so that the total size of the model is reduced and vertical dimensions are sufficiently large to preserve hydraulic similitude and prevent viscous and surface tension effects from influencing model results.

(a) Applicability. Distorted models are used to define the three-dimensional hydrodynamics of the entire prototype system for various operating scenarios. They have been used extensively in the study of large rivers and estuarine systems.

(b) Limitations. With distorted models, as with undistorted models, it is assumed that similitude exists between the prototype and the physical model. It is also assumed that the important basin characteristics can be reproduced in the laboratory. Because the vertical and horizontal dimensions are scaled differently, the longitudinal slopes differ and rates of vertical and transverse mixing are distorted, thereby limiting applications to situations in which these processes are not significant. In addition, the models are designed and operated to investigate only one process at a time, and synergistic effects due to other hydrometeorological processes such as wind are not included. The model cannot be used to analyze conditions outside the calibration range.

c. Implementation and Interpretation. Physical model studies must be designed, constructed, and operated by qualified individuals specializing in the process and experiment under investigation. It may take a year or longer to design, construct, and complete a study. Data acquisition and analyses may require specialized equipment that is not routinely available. Model results must be interpreted with knowledge of model design, scaling, and study objectives. The results should not be applied outside the experimental range. The WES should be consulted on these types of studies.

CHAPTER 5

WATER QUALITY DATA COLLECTION AND ANALYSIS

Section I. Introduction

5-1. Purpose. This chapter provides guidance on collecting water quality data, database management, and data presentation. It is intended for scientists and engineers responsible for compiling existing data from non-Corps sources, establishing Corps data collection programs, and analyzing data for District or Division water quality management programs.

5-2. Overview. Since results from data-gathering efforts from non-Corps sources and Corps water quality sampling programs are used to evaluate both existing reservoir water quality conditions and the attainment of reservoir water quality objectives, these assessment programs must be well conceived and scientifically sound and must provide representative water quality data.

a. Objectives of the Study. A clear, concise statement of the study objectives is essential (Chapter 3). Without a statement of objectives, it is unlikely that the right questions will be addressed, the appropriate data collected, or the proper analyses performed. Sampling programs are expensive, so it is important to ensure that the data collected are useful. As data are analyzed and the water quality concerns and processes are better understood, water quality objectives may be clearly defined and the sampling program modified to address areas of uncertainty or concern.

b. Sampling Objectives. The sampling program objectives must be specifically defined and documented to ensure successful implementation and completion of the program. To a large extent, defining the objectives will determine the data needs in the program. The importance of the interrelated factors such as objectives, system characteristics, and degree of precision should also be considered (Ref. 64).

c. Population to Be Characterized. The term population is defined as the assemblage from which the sample is taken. There is the overall or general population and a sample population. The general population represents the entire set of measurements about which inferences or conclusions are to be made (e.g., the entire reservoir or the entire algal assemblage). The sample population (i.e., measurement of that constituent in the water quality samples) represents a subset of measurements taken from the general population. The subset is used to gain information and make inferences about the overall population. It is important that the sampled population be representative of the general population. The purpose of sampling design is to ensure the limited number of samples collected (e.g., 25-50 one-liter samples per sampling trip) provide adequate information about the overall population characteristics (e.g., total amount of that constituent in a reservoir containing about 10^{11} liters of water). The initial sample population, then, must not become altered or redefined during the sampling program.

d. Characteristics to be Measured. After the general population has been clearly defined, all relevant population characteristics should be identified and subdivided into essential or ancillary categories. The key to reducing the uncertainty surrounding project water quality is to collect samples pertaining to essential population characteristics. Sampling effort on ancillary characteristics that indirectly affect or are of secondary importance in attaining the study objectives should be minimized. Identifying these characteristics can be a difficult task but is an important requirement to ensure appropriate use of resources (see Chapter 2 for additional information).

e. Degree of Precision. All measurements have inherent errors or uncertainty because only part of the population has been measured. The degree of uncertainty can be reduced by taking more samples and using more precise techniques. However, budgetary constraints ultimately limit these approaches. Precision and cost are essential and interrelated elements in all sampling programs since precision influences cost. If the desired precision results in excessive cost, the precision of some or all variables may have to be reduced. Initial estimates of desired precision should reflect the analytical precision of the individual constituent. Estimates of analytical precision have been determined by the American Public Health Association (APHA) (Ref. 48) and the US Geological Survey (USGS) (Ref. 46).

f. Selection Criteria. The criteria established for selecting a sampling design represent a compromise between the desired precision and budget constraints. With any sampling design, the sample size is dependent on precision, cost, and variability of the estimator used to describe a population characteristic. When the sample size for each design has been determined, relative costs and time involved for each design can be computed and decisions relative to the acceptable sampling design can be made.

g. Use of Existing Data. As part of determining the data needs for an assessment, a screening of existing data should be conducted (see Chapter 4, Section I). Using available data can save effort and money; however, an appropriate level of confidence must be built into these data (e.g., Is the source known? Were the methods of collection and analysis used compatible with the level of detail and quality identified in the objectives of the proposed assessment?). In some cases, existing data may be used in the assessment or they may provide an "order of magnitude" reference from which to begin data collection for the assessment. In instances where little is known about the data, it is better to collect data specifically for the assessment.

Section II. Field Data Collection

5-3. Principles. Green (Ref. 69) cites ten basic principles of sampling design and statistical analysis for environmental studies that should be considered in developing a reservoir water quality assessment study. These principles are:

a. Clearly identify the objectives. An investigator must be able to describe clearly to someone else the purpose of the investigation. The results can only be as coherent and as comprehensible as the initial definition of the problem.

b. Make sure the investigator takes replicate samples to get an estimate of the variability and uncertainty in the sampling program.

c. Make sure the investigator has a random sampling program.

d. To test whether a condition has an effect, collect samples both where the condition is present and where the condition is absent. It is also important to collect samples where other factors are similar. An effect can only be demonstrated by comparison with a control.

e. Carry out preliminary sampling to provide a basis for evaluation of sampling design and statistical analysis options. Skipping this step in an effort to save time usually is unproductive.

f. Verify that the sampling device or method is sampling the characteristics, area, variables, or organisms that are needed, with equal and adequate efficiency over the entire range of sampling conditions to be encountered. Variations in sampling efficiency of anaerobic versus aerobic samples from area to area can, for example, bias comparisons.

g. If the area to be sampled has a large-scale environmental pattern, break the area up into relatively homogeneous subareas and allocate samples to each in proportion to the size of the subarea.

h. Verify that the sample unit size is appropriate to the size, densities, and spatial distributions of the variable that is being sampled. Also, estimate the number of replicate samples required to obtain the precision wanted.

i. Test the data to determine whether the error variation is homogeneous, normally distributed, and independent of the mean. If it is not, as may be the case for most field data, then appropriately transform the data, use a distribution-free (nonparametric) procedure, use an appropriate sequential sampling design, or test against simulated data.

j. Having chosen the best statistical method to test one's hypothesis, it is important to stick with the result. An unexpected or undesired result is not a valid reason for rejecting the method and seeking a "better" one.

5-4. Sampling Designs. The study objectives, specified precision, and cost usually dictate which sampling design is implemented. Since the purpose of the sampling design is to characterize some aspects of reservoir water quality, characteristics of the general population in the reservoir must be considered. Longitudinal gradients, tributary sources, and other patterns can increase the variability in the data. The sampling design should consider these sources of variability at the beginning of the sampling program so procedures can be incorporated to minimize their impact during the later data analysis and interpretation phases. This can be accomplished through various types of random sampling.

a. Simple Random Sampling. Simple random sampling is a method of selecting n sampling units out of the total N units so that every sampling unit has an equal chance of being selected. With reservoir water quality sampling programs, the sampling units usually correspond to sampling stations or locations. Stations can be selected by superimposing a grid system on the reservoir water surface and selecting locations at random. Sampling depths should be selected at random if vertical resolution is desired. The assumption of homogeneity among sampling units is critical in the simple random sampling scheme. If the population cannot be divided into N homogeneous sampling units, then simple random sampling should not be used. However, if the assumption is valid (i.e., the reservoir is relatively homogeneous), this approach provides an efficient, cost-effective procedure. Assessing the variability in surface chlorophyll concentrations may use a simple random sampling approach.

(1) Estimation of sample size. The number of samples to be collected depends on the variability of the population characteristics that are being estimated and the desired precision of the estimate. Estimates of variability can be obtained by reviewing existing data or by conducting surveys or reconnaissance studies on the reservoir. The general formula for sample size determination is:

$$n = \frac{t^2 s^2}{d^2}$$

where

n = number of samples

t = appropriate value from Student's t distribution

s^2 = sample variance

d = desired precision about the mean

Since Student's t-value varies as a function of n, a t-value for 30 degrees of freedom can be used to initialize the procedure. The formula, then, can be evaluated iteratively, substituting the appropriate t-value for each predicted n until the iterative procedure converges (see Appendix C).

(2) Sample size determination for multiple characteristics. If sampling objectives are to obtain information on several water quality variables,

sample size determination becomes more tedious to achieve the desired precision for each variable. Sample size estimates must be determined for each constituent and the maximum estimates chosen as the sample size for the sampling plan. For those variables that require significantly fewer samples to achieve the desired precision, a randomization scheme can be constructed to subsample the sampling units. Another approach is to estimate the sample size only for the most critical variables. Although this does not guarantee the desired precision for all constituents, precision for the most critical constituents can be achieved; precision for the other variables can be estimated and will be available for future use and analyses.

b. Stratified Random Sampling. With stratified random sampling, the population of N units is divided into subpopulations of N_1, $N_2 \ldots N_L$ units, respectively. The subpopulations are nonoverlapping and together comprise the entire population, so that

$$N_1 + N_2 + \ldots + N_L = N$$

These subpopulations are called strata. To obtain maximum benefit from stratification, the values of N_j $(j = 1, 2 \ldots L)$ must be known. In a typical water quality sampling program, strata may be the epilimnion, metalimnion, and hypolimnion; or the headwater, main pool, and near-dam locations; or a combination of these or other designations. Once the strata have been determined, samples are independently drawn from each stratum. The sample sizes within each stratum are denoted by n_1, $n_2 \ldots n_L$.

(1) Estimation of sample size. Stratification of the population produces a highly efficient sample allocation scheme. A general formula for sample size distribution is

$$n = \frac{(\Sigma W_i S_i)^2}{d^2/t^2}$$

where

n = total number of samples

W_i = weighting factor for stratum i (e.g., ratio of volume of stratum to total volume or surface area of stratum to total surface area)

S_i = standard deviation of samples in stratum i

d = desired precision

t = appropriate Student's t-value

Sample size within a stratum can be determined by

$$\frac{n_i}{n} = \frac{W_i S_i}{\Sigma(W_i S_i)}$$

Stratified random sampling in reservoirs usually requires fewer samples than random sampling to obtain the same precision (Appendix C).

(2) Optimum allocation. The sample size allocation scheme for each individual stratum can incorporate cost, if sampling costs vary over strata. The objective is to allocate samples to minimize costs. The simplest cost function is of the form

$$C = C_o + \Sigma C_i N_i$$

where

C = total cost

C_o = fixed cost (e.g., travel, per diem, etc., per sampling trip)

C_i = cost per sample within stratum i

N_i = the number of samples within stratum i

With this as the underlying cost function, the n_i's from the stratified sampling formula can be determined by

$$n_i = n \left[\frac{W_i S_i / C_i}{\Sigma(W_i S_i / C_i)} \right]$$

An example of a cost-precision-probability matrix is shown in Table 5-1. A similar table can be developed for other variables and used to optimize the sampling scheme to retain precision on critical constituents and reduce precision or probability requirements on desired constituents to satisfy funding constraints.

(3) Fixed sample numbers. The sampling formula can also be used to assess the loss of precision if fixed numbers of samples are collected at each station. It is unrealistic to expect a field crew to collect nine phosphorus samples, three turbidity samples, and twelve chlorophyll samples at station 3 (Table 5-1) with a variable number of samples at other stations. If it is determined that six samples will be collected from the epilimnion, four samples from the metalimnion, and eight samples from the hypolimnion at every station, the precision for each constituent can be determined by rearranging the sampling formula as

TABLE 5-1

Example of a Sampling Matrix to Optimize Sample Numbers, Precision, and Cost (after Ref. 104)

		Station 3						Station 10 or 12						Station 14 or 15					
Total Phosphorus	Unit Cost	$13						$13						$13					
	Mean[1]	9 µg P/ℓ						20 µg P/ℓ						34 µg P/ℓ					
	Precision[2]	±50%			±100%			±25%			±50%			±15%			±30%		
	Probability	95%	90%	80%	95%	90%	80%	95%	90%	80%	95%	90%	80%	95%	90%	80%	95%	90%	80%
	Sample No.	12	9	5	4	4	3	18	13	8	6	5	3	32	23	14	10	7	5
	Total Cost[3]	156	117	65	52	52	39	234	169	104	78	65	39	416	299	182	130	91	65
Turbidity	Unit Cost	$3						$3						$3					
	Mean	1.3 NTU's						5.3 NTU's						5.3 NTU's					
	Precision	±50%			±100%			±20%			±40%			±20%			±40%		
	Probability	95%	90%	80%	95%	90%	80%	95%	90%	80%	95%	90%	80%	95%	90%	80%	95%	90%	80%
	Sample No.	13	10	6	5	4	3	8	6	4	4	2	1	8	6	4	4	2	1
	Total Cost	39	39	18	15	12	9	24	18	12	12	6	3	24	18	12	12	6	3
Chlorophyll	Unit Cost	$20						$20						$20					
	Mean	2 µg/ℓ						7 µg/ℓ						11 µg/ℓ					
	Precision	±25%			±50%			±25%			±50%			±15%			±30%		
	Probability	95%	90%	80%	95%	90%	80%	95%	90%	80%	95%	90%	80%	95%	90%	80%	95%	90%	80%
	Sample No.	19	13	9	6	5	3	13	10	6	5	4	3	21	15	9	7	5	4
	Total Cost	380	260	180	120	100	60	260	200	120	100	80	60	420	300	180	140	100	80

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an values are those expected based on three sampling dates.

ent precision based on approximate levels of analytical precision for each test or requirements of the study.

cost calculated as product of unit cost and sample number.

$$d = \frac{ts}{\sqrt{n}}$$

for the random sampling formula, and for the stratified random sampling formula

$$d = \frac{(\Sigma W_i S_i)t}{\sqrt{n}}$$

While the desired precision may not be obtained for every water quality constituent, the precision and uncertainty associated with each constituent can be determined and factored into decisions related to water quality.

c. Other Techniques. The two sampling approaches discussed in the preceding paragraphs are the most commonly used. However, other sampling schemes are available and described in the technical literature. If the two approaches discussed above are not acceptable, then such schemes as systematic sampling, one-stage sampling, two-stage sampling, etc., could be used. More complete descriptions of these and other techniques can be found in Snedecor and Cochran (Ref. 99) or Winer (Ref. 111).

5-5. Field Sampling and Analysis. Field sampling procedures, methodology, and analyses have been discussed in detail by APHA (Ref. 48), EPA (Ref. 39), Likens and Wetzel (Ref. 86), and USGS (Ref. 46). Several excellent points on field sampling are made by Kittrell and West (Ref. 84), although stream sampling is emphasized. This paragraph follows the discussion in the National Handbook of Recommended Methods for Water-Data Acquisition (Ref. 46). On field sampling activities, major topics include obtaining representative samples, maintaining quality control and assurance in the field, and selecting field personnel.

a. Representative Samples. A number of factors are important in obtaining representative water quality samples. These factors include sampling objectives; station location, depth, and frequency; equipment; sample variables; sample handling and preservation; and sample identification.

(1) Sampling objectives. The sampling program should be dictated by the sampling objectives. Monitoring programs, water quality surveys, intensive sampling, or regulatory sampling may have objectives that require different field sampling designs and procedures. For example, water quality surveys may have lower precision requirements and a more restricted budget than intensive sampling programs, and therefore require different sampling designs. Procedures for maintaining the chain of custody, for example, are not critical in most monitoring programs but are extremely critical in addressing legal questions. Any change in objectives must be accompanied by a review of the sampling program and can necessitate a change in the sampling approach.

(2) Sampling locations. Sampling station locations are influenced by the sampling objectives, hydrology, reservoir and hydraulic outlet geometry, point and nonpoint sources, accessibility, available equipment and facilities, and personnel. Flow estimates must accompany all tributary and reservoir release water quality samples. Tributary sampling stations, therefore, may be selected to correspond with gaging stations. If this is not possible, flow must be measured at the time of sampling. Sampling stations should be located in representative areas of the reservoir and are dictated by the sampling program objectives. For example, estimating mean or average conditions for the reservoir may result in samples collected proportional to reservoir volume. The greatest number of samples would be collected from the mixed layer since this represents the greatest volume in the reservoir, with a progressive decrease in the number of samples collected with depth. Longitudinal and lateral variability, as well as vertical variations in many water quality constituents, may be considered in determining station locations. At a minimum, samples should be collected in the inflow, the outflow, and at a representative station in the pool.

(a) Longitudinal variation. Many reservoirs have areas with distinct water quality conditions, such as the headwater, zone of transition, or lacustrine area. The extent of these areas should be identified before locating sampling stations. The zone of transition is a function of the plunge point depth, so the minimum and maximum depths for the plunge point can be computed to delineate the headwater and lacustrine areas. Formulations for estimating the plunge point depth are available (Ref. 12). Annual high and low quartile flows (i.e., 75 and 25 percent of median annual flow) can be used to predict the maximum and minimum plunge point depths, respectively, in the reservoir. Stations located upstream of the minimum plunge point depth should be in the headwater area, stations located downstream from the maximum plunge point depth should be in the lacustrine, while stations in between the minimum and maximum plunge point depths can be used to characterize the zone of transition. This longitudinal variability also may occur from the headwater of a cove to its confluence with the main body of the reservoir.

(b) Lateral variability. Tributary inflows tend to follow the old channel or thalweg through the reservoir both as underflows and interflows. The zone of conveyance for flow and associated constituents may not extend across the reservoir. This can result in lateral differences across the reservoir. Initial sampling efforts should investigate potential lateral variability by sampling over the thalweg and at alternative locations across the reservoir. This can be evaluated initially by specific conductivity measured laterally across the reservoir. If conductivity is relatively constant, most dissolved constituents probably are also. Transmissometer readings across the reservoir may indicate particulate constituent variability. Established sediment survey transects provide permanent reference points, transect geometry, and representative reservoir areas and should be used initially.

(c) Bridges. Bridges are typically selected as sampling sites for reservoirs because of accessibility and convenience. Bridges crossing the reservoir in the headwater area may be satisfactory sites since vertical stratification is usually minimal while boat access may be limited. Bridges, however, are generally located or constructed at reservoir constrictions. These localized constrictions may result in localized velocity increases that disrupt stratification patterns and result in an altered water quality regime around the bridge. Therefore, sampling from bridges may not provide representative data for reservoir areas where vertical stratification occurs. Bridges or other constrictions also may effectively isolate various parts of the reservoir. Backwater effects and altered sedimentation regimes may result in different water quality in these areas and may require sampling stations to characterize water quality in this area.

(3) Sample depths. Sampling objectives, reservoir geometry, hydraulic outlet design, hydrology, stratification patterns, and reservoir operation all influence selection of appropriate sampling depths. A fixed-depth sampling approach generally is adequate if sufficient samples are collected to characterize water quality throughout the water column. Fixed sampling depths from the reservoir water surface represent the most common approach and permit seasonal and year-to-year water quality comparisons at and among stations in monitoring programs. Using the reservoir water surface as the reference point also permits comparisons, even with large variations in the water surface elevation. It is recommended that sampling depths be selected to characterize the epilimnetic, metalimnetic, and hypolimnetic stratification zones while integrated samples may be considered to characterize the upper mixed layer and reduce the number of epilimnetic samples. Since development and deepening of the thermocline during the stratification period changes the mixed layer depth, integrated samples may be collected based on the average mixed layer depth for this period. At least three samples--surface, middepth, and bottom--should be collected in reservoirs that generally remain well mixed, since these reservoirs may intermittently stratify. Water quality conditions may change drastically during these intermittently stratified periods. Middepth and bottom samples are particularly important in these reservoirs during ice cover when oxygen concentrations may be depleted. Anoxic conditions during winter are typically initiated at the sediment/water interface.

(4) Sampling frequency. Sampling frequency or sampling times and dates are critical in obtaining representative reservoir water quality data. Fixed-interval sampling may miss the important hydrologic and limnological events occurring in a reservoir. For example, a typical monthly sampling program (e.g., every 30 days) in the Caddo River tributary to DeGray Lake during 1977 would not have incorporated storm flow in any of the samples (Figure 5-1). The majority of nutrient, suspended sediment, and other constituent loading, however, may occur during elevated flow periods. The sampling intervals should incorporate the important hydrological and limnological events affecting reservoir water quality (Table 5-2). The same total number of samples may be collected in either a fixed-interval, monthly sampling program or variable-interval sampling program, but more information per sample and more insight into reservoir water quality can be obtained from variable-interval sampling.

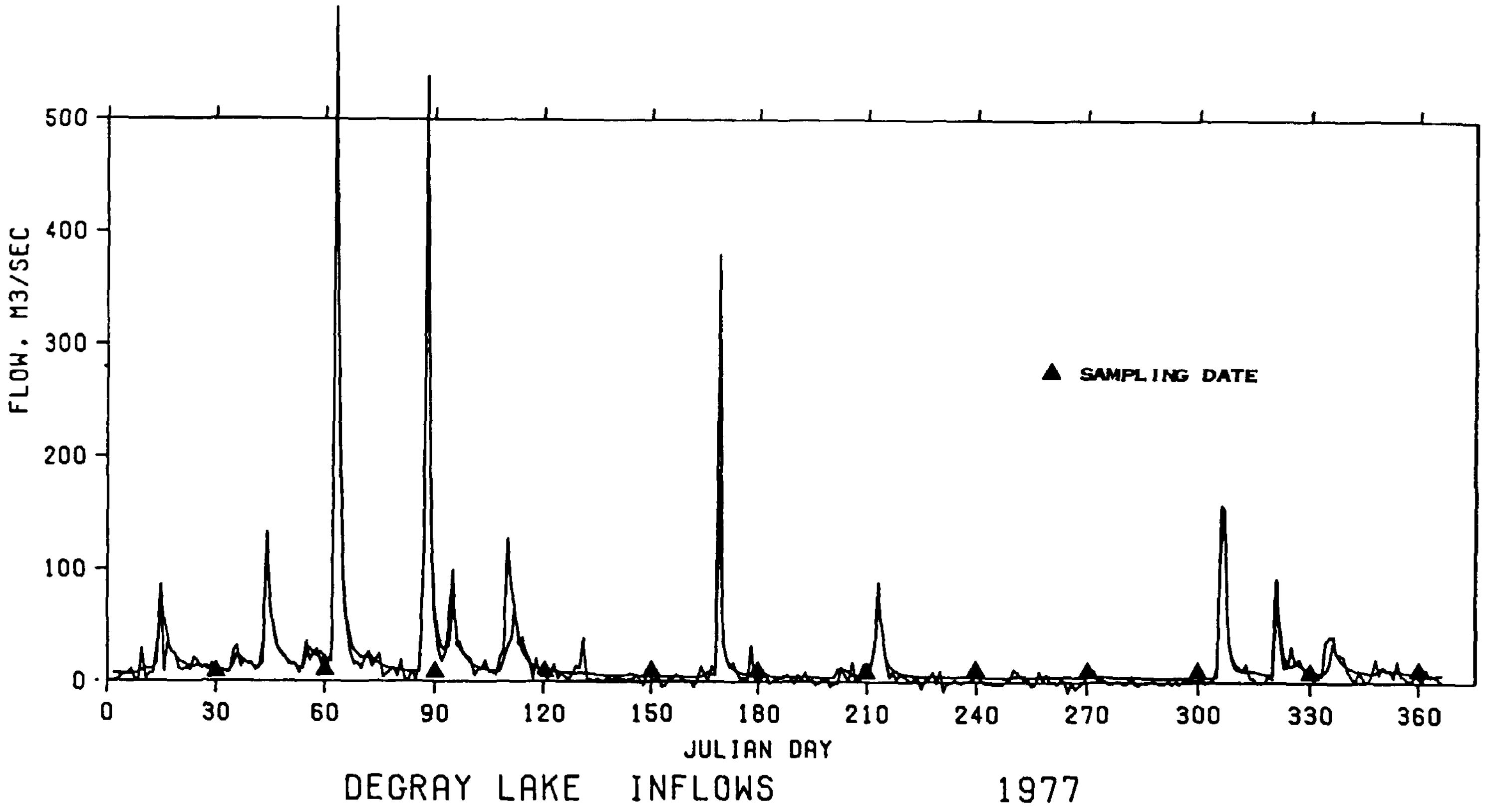


Figure 5-1. Potential bias in sampling program using a fixed interval (e.g., 30-day) sampling period

TABLE 5-2

Example of Sampling Intervals Corresponding with Hydrologic and Limnological Periods

Date Sampled	Event
Mid-March	Isothermal or late winter ice period
Mid-late April/ mid-May	Elevated flow; early stratification
Early-late June/ mid-July	Increased biological activity and public use
Early-late August	Strong stratification, low runoff
Late September/ mid-October	Anoxic conditions, plankton blooms, low flow
Mid-late November	Thermocline deepening and turnover; isothermal, initial winter conditions

Similar information can be obtained by combining special-interval or event sampling with a fixed-interval sampling program.

(5) Sampling equipment. Field gear typically used in water quality sampling is described in APHA (Ref. 48), USGS (Ref. 46), and Likens and Wetzel (Ref. 86) and is discussed and demonstrated through training courses offered by the EPA, USGS, and other Federal agencies. The use of sampling equipment, like any other analytical procedures or techniques, requires that assumptions and limitations be considered. Metal water samplers, for example, should not be used to obtain water samples for metal analyses or primary productivity measurements. Plastic samplers and bottles may interfere with organic and certain trace metal analyses. Two grab samplers used extensively in many field sampling programs are the Van Dorn and Kemmerer samplers. These samplers can collect water samples at any given depth or point in the water column. Samples also may be collected by pumping water from a given depth to the surface for collection. Pumped samples are advantageous when large numbers of samples are to be collected, the reservoir is not exceptionally deep (e.g., <150 feet), or anoxic samples are to be collected. When collecting pumped samples, the hoses must be allowed to clear and flush the water from a previous depth before filling the sample containers. In situ measurements can be made using sensor probes and digital or analog readout or recording devices. These instruments can measure temperature, DO, pH, orthophosphate, specific conductance, several specific cations and anions, and light penetration. While grab samplers, pump systems, and in situ probes all may be required to obtain representative water quality data, their use must be based on a clear understanding of the data needs, data use in water quality management, and characteristics of the reservoir. Regardless of the standardization or accepted use of sampling gear, all field sampling equipment, from a thermistor to a Kemmerer sampler, have idiosyncrasies. User experience and familiarity are critical in obtaining representative water quality samples or measurements.

(6) Sample variables. The water quality variables incorporated in the sampling program are a function of the project purposes, sampling objectives, applicable water quality standards or criteria, facilities and equipment, personnel, and funding constraints. Some water quality constituents typically measured in reservoir water quality sampling programs are listed in Table 5-3. Incorporating variables that can be measured in situ or surrogate variables can provide some sampling economies. It must be recognized, however, that surrogate variables provide only inferential information and not direct estimates for the primary variable of interest.

(a) In situ variables. Water temperature represents the most common in situ variable measured. Incorporating the capability to measure DO, specific conductivity, and pH in the same instrument adds little to the overall cost of the sampling program but can add significantly more information about reservoir water quality. The time required to measure these additional constituents also is insignificant. In situ data can be collected using remote sensing techniques or continuous monitoring. Remote sensing includes the

TABLE 5-3

Typical Water Quality Variables Measured in Reservoirs and the Sample Handling and Preservation Requirements

Determination	Container[1]	Min. Sample Size, ml	Preservation	Max. Storage Time Recommended/Regulatory
Acidity	P,G(B)	100	Refrigerate[2]	24 hr/14 days
Alkalinity	P,G	200	Refrigerate	24 hr/14 days
Carbon, organic total	G	100	Analyze immediately; or refrigerate and add H_2SO_4 to pH <2	7 days/28 days
Carbon dioxide	P,G	100	Analyze immediately	
Chlorophyll	P,G	500	30 days in dark; freeze	30 days/--
Color	P,G	500	Refrigerate	48 hr/48 hr
Conductivity	P,G	500	Refrigerate	28 days/28 days
Hardness	P,G	100	Add HNO_3 to pH <2	6 months/6 months
Metals, general	P(A),G(A)	-	For dissolved metals filter immediately, add HNO_3 to pH <2	6 months/6 months
Nitrogen:				
Ammonia	P,G	500	Analyze as soon as possible or add H_2SO_4 to pH <2; refrigerate	7 days/28 days
Nitrate	P,G	100	Add H_2SO_4 to pH <2	48 hr/48 hr
Nitrate, nitrite	P,G	200	Analyze as soon as possible or refrigerate; or freeze at -20° C	none/28 days
Organic, Kjeldahl	P,G	500	Refrigerate; add H_2SO_4 to pH <2	7 days/28 days
Oxygen dissolved:	G.BOD bottle	300	Analyze immediately	0.5 hr/1 hr
Electrode			Titration may be delayed after acidification	8 hr/8 hr
pH	P,G	-	Analyze immediately	2 hr/2 hr
Phosphate	G(A)	100	For dissolved phosphate forms filter immediately, refrigerate; freeze at 10° C	48 hr/48 hr
Residue	P,G	-	Refrigerate	7 days/7-14 days
Salinity	G.wax seal	240	Analyze immediately or use wax seal	6 months/--
Silica	P	-	Refrigerate, do not freeze	28 days/28 days
Sulfate	P,G	-	Refrigerate	28 days/28 days
Sulfide	P,G	100	Refrigerate; add 4 drops 2 N zinc acetate/100 ml	28 days/28 days
Temperature	P,G	-	Analyze immediately	
Turbidity	P,G	-	Analyze same day; store in dark up to 24 hr	24 hr/48 hr

SOURCE: Ref. 48.

[1] P = plastic (polyethylene or equivalent); G = glass; (A) = acid rinsed; (B) = borosilicate.

[2] Refrigeration = storage at 4° C.

use of both aerial and satellite imagery to collect water quality information. Engineer Pamphlet 70-1-1 fully explains the applications of remote sensing and should be referenced for specific information. The field sampling program can provide the data required to correlate spectral densities with water quality. Remote sensing can provide information on surface variability in water quality constituents, reservoir circulation patterns, inflow mixing processes, and other surface phenomena. An economical approach to obtaining continuous or time-series data for selected water quality constituents is to employ continuous water quality monitors. Continuous monitors may collect single- or multiple-constituent measurements in situ with a probe or sensing unit. Water temperature is the water quality constituent typically monitored, with DO, pH, and specific conductance also commonly measured. Continuous monitors have generally been used to monitor inflow and release water quality constituents since vertical gradients are weak and the sensing unit for in situ measurements or pump intake can be located at a representative point in the stream. Continuously monitoring reservoir water quality may require multiple sensors or pump intakes located vertically throughout the water column. For some applications, this can be the most economical means of obtaining continuous or time-series data. Presently, however, continuous monitors are applicable primarily for monitoring certain inflow and release water quality characteristics. Continuous monitoring is not synonymous with maintenance-free data collection. Continuous monitors require routine maintenance, generally on a weekly or biweekly basis, to ensure the instruments are functioning and remaining within calibration tolerances. Continuous monitors, units of measure, definitions, and considerations have been described in detail by the USGS (Ref. 46). The US Environmental Protection Agency (Ref. 40) and Schofield (Ref. 97) have reviewed automatic samplers and sampler design. These documents should be reviewed for additional information on continuous monitors. Data reduction and data management should receive careful consideration for monitoring systems.

(b) Surrogate variables. Surrogate variables can be sampled to provide information on other variables of primary interest. Specific conductivity and chlorophyll a are two examples of surrogate variables. Specific conductivity generally has a high correlation with total dissolved solids (TDS) concentrations. Measurement of TDS may be of major interest for irrigation purposes, for example, but is more expensive and time-consuming than the measurement of conductivity. This correlation should be determined for each reservoir since the correlation may vary among reservoirs. Certain phytoplankton species can cause taste and odor problems, clog water treatment plant filters, and create an unaesthetic appearance in the reservoir. Species enumeration and counting, however, can require special equipment and expertise that are not available in District or Division offices. Chlorophyll measurements can provide general information on the phytoplankton community but will not indicate the particular species affecting water quality.

(c) Specific variables. In situ and surrogate variables are appropriate for water quality surveys, but sampling programs designed to provide specific information for reservoir water quality management should supplement these variables with other constituents that relate to specific management objectives. At a minimum, in situ variables and Secchi depth should be measured at every sampling station on every sampling date, since these measurements add little to the cost but markedly increase knowledge about reservoir water quality. For example, sediment quantity and quality markedly influence reservoir water quality. Reservoir sedimentation surveys are periodically conducted to evaluate the loss of reservoir storage. An intensive water quality survey investigating longitudinal, lateral, and vertical water quality conditions should be conducted during July or August of the same year as the sedimentation survey. In situ variables, a representative nutrient, and chlorophyll should be measured, at a minimum, at selected locations along the sediment survey transects. These studies can provide a datum for comparisons among reservoir areas and among years.

(7) Sample handling and preservation. Appropriate sample handling and preservation is essential to ensure data quality. Standard Methods (APHA) (Ref. 48), EPA (Refs. 41, 43), Plumb (Ref. 20), and USGS (Ref. 46) discuss appropriate containers and proper preservation techniques for various water quality constituents and should be reviewed prior to field sampling (see also Table 5-3). Factors to be considered, in addition to those specifically mentioned in these references, include:

(a) Clean plastic containers are typically used for inorganic samples, with glass containers used for organic analyses. The caps or container lids, however, also must be of similar material to avoid sample contamination. Plastic lids or plastic liners and rubber stoppers can contaminate samples in glass bottles even though the surface area of the lid may be small.

(b) Proper sample preservation is critical if accurate and representative results are to be obtained from the sampling efforts. In general, all samples are placed on ice in the dark, even if additional preservation is required. Metal samples are generally preserved with nitric acid, nutrient samples with sulfuric acid, and organic samples through chilling.

(c) The desired form of a chemical species to be measured must be determined prior to preservation. For example, dissolved chemical species may require immediate field filtration prior to acidification. Acidification in the field, followed by laboratory filtration, can produce artificially high concentrations of dissolved elements. Appropriate filter pore sizes have been determined by APHA (Ref. 48).

(d) Analyses should be initiated as soon as possible after collection to avoid sample deterioration. Recommended and regulatory holding times are given in Table 5-3; these are based on Standard Methods (Ref. 48) and the USGS Handbook (Ref. 46).

(e) Any sample containing ≤ 0.5 mg/ℓ DO as measured onsite with a DO membrane electrode should be considered anaerobic. Anaerobic samples for those chemical parameters that may be either oxidized or precipitated on aeration can be pumped from the appropriate depths, through an acid-washed membrane filter if needed, into sample bottles containing the appropriate preservation. The sample bottom should be filled to capacity, then capped with an airtight lid.

(8) Sample identification. Proper sample identification in the field can eliminate subsequent problems in laboratory and statistical analyses. At a minimum, the date, reservoir station number, depth, preservation type, and replicate or split sample should be recorded on the sample. Before use in field sampling, all marking inks or fluids, labels, and containers should be tested under field conditions (i.e., immersion, agitation, preservation, spills) for container leakage, label and ink removal, and breakage. All previous labels or markings on sample containers should be removed prior to reuse. A separate log should be maintained that identifies the individual(s) collecting the samples, weather conditions, sample appearance, problems, unusual conditions, or other observations that may assist in interpreting the water quality data.

b. Field Quality Control and Assurance. Quality control (QC) and quality assurance (QA) must originate in the field if subsequent laboratory analyses are to provide accurate and representative data. Laboratory QA and QC programs have been established, but guidance on field QA and QC programs, although just as essential, is relatively new (Ref. 46). Field QA and QC can be improved through sampling standardization, sample preservation and replication, instrument calibration, and accurate records maintenance.

(1) Standardization. A standard approach to field sampling that incorporates checklists and a consistent sampling protocol can minimize omission and duplication errors during sample collection. This standard approach includes: a checklist of equipment and supplies required for each sampling trip; a specified location for the equipment and supplies in the sampling vehicle or boat; standard procedures for sample collection, filtration, and preservation; and routine procedures for delivering samples to the laboratory. One example of a standard procedure for sample preservation is color-coded labels for bottles (e.g., blue label for chilling, red for H_2SO_4 addition, and yellow for HNO_3 preservation). These codes can be combined (e.g., blue and red dot labels indicate chilling and H_2SO_4) or modified to indicate filtered versus nonfiltered samples. Standardization can also help ensure consistent results during personnel changes. Standard approaches, however, should not be confused with a rigid, inflexible program. Flexibility must be maintained to reflect changing program objectives and improved techniques and equipment. This flexibility also should allow for storm events and unusual field conditions or situations that may require collection of additional samples.

(2) Preservation and replication. A QC/QA program should quantitatively account for constituent additions or losses during sample preservation and determine the contribution of sampling error to the total sample error. Addition of known concentrations of reference standard solutions to field samples

should allow for measurement of error due to preservation, sorption, or interference. Sampling error also can be assessed through replication and split sampling. Replication involves collection of two or more distinct samples from the same location. Split sampling involves dividing a single sample among two or more sample containers for subsequent analysis. Estimates of sampling variability can be determined if as few as 10 to 15 percent of the samples receive known constituent additions and are replicated or split. Once the sources of error have been determined, sampling programs can be modified to minimize these errors.

(3) Instrument calibration. All instruments require periodic calibration. Changes in temperature, humidity, pressure, or other environmental factors can influence instrument calibration. In addition, transporting the instrument in a vehicle or boat can loosen sensitivity controls or connections and affect measurement accuracy. Calibration should be checked before and after each sampling trip, even for relatively stable probes such as temperature or specific conductance. Some instruments have internal temperature corrections, so temperature calibration can affect the accuracy of other constituent measurements. The precision and sensitivity of the instruments should be determined periodically for existing equipment and before initial field use for new equipment. Manufacturer's detection limits, precision, and sensitivity estimates are generally measured under ideal conditions and may not be applicable under field conditions. If two or more different manufacturers' instruments are used for measurements, they should be compared under field conditions even if the instruments were calibrated similarly. Instruments that cannot be calibrated should be used with caution. The manufacturers' manuals, Standard Methods (Ref. 48) and USGS Handbook (Ref. 46) should be consulted for specific recommendations on calibration.

(4) Records. Operating logs and records of measured field data, calibration curves, corrective actions, and QA activities should be maintained. Field personnel should be provided with a specified protocol for recording field observations, including content, format, names of the individuals collecting the data, and names of the individuals checking the validity of the data. These records should be identified and readily available for reference. Duplicate records may be a consideration. Guidelines should be established for record retention, duration, location, and assigned responsibility for each project. These guidelines and the retention period should be based on the sampling program design and objectives and the use of the data. Methodology generally changes significantly over a 10-year period and may influence data comparability over long time periods. Ten years may represent a minimum retention period for most monitoring and survey records.

c. Field Personnel. Since planning, engineering, and operational decisions that involve large expenditures of funds can be influenced by water quality data, these data must accurately represent the water quality conditions in the reservoir. The success of any sampling program ultimately depends upon competent laboratory and field personnel. This competence can be developed and maintained through on-the-job and formal training.

5-6. Laboratory Analysis. Laboratory analytical procedures and methodology are discussed in detail in EPA (Ref. 43), APHA Standard Methods (Ref. 48), and the USGS Handbook (Ref. 46). These references should be consulted for specific details on all procedures. Many laboratory analyses for Corps District and Division offices are contracted. Reference 42 discusses procedures for evaluating and monitoring laboratories. Engler (Ref. 65) provides guidance on contracting for laboratory analyses, while Peddicord (Ref. 19) provides guidance on contracting biological and chemical evaluations. Although the latter is directed toward dredged material, it discusses the contracting process, laboratory selection, contract management, and QA considerations. Contract management must be an active process since sample analysis represents the most important phase of the project. The effort put into contract management is directly proportional to the quality of the final product. The contract should have the flexibility to incorporate additional unscheduled sampling. Samples collected during the occurrence of storm events or other relatively rare situations in the field can provide the data and insight required for the development of better management approaches for reservoir water quality.

Section III. Database Management

5-7. Database Management Systems.

a. General. There are two major types of database management systems: general purpose or long-term databases, and specific water quality databases. General purpose databases such as STORET focus on information storage and retrieval strategies rather than on analysis of retrieved data sets. Specific water quality databases emphasize analytical and display routines. Short-term intensive studies or process-oriented studies typically require specific water quality databases.

b. General Purpose Database Management Systems. Water quality databases that are developed and used for general purposes strongly parallel the classical approach to database development and implementation strategies. General purpose database management systems focus primarily on database construction and retrieval strategies. Corps Divisions and Districts primarily use four data storage and retrieval systems: STORET, WATSTORE, AURAS, and SIR. Other systems, including UPGRADE, NAWDEX, and some that are commercially available, are also discussed in the following paragraphs.

(1) STORET, developed and operated by the EPA, maintains its water quality database on IBM equipment and is available to any user with the proper identification and access requirements. The EPA places few restrictions on its use and provides no automated QA controls over data entered into the system. Users inexperienced in the use of computers may have some difficulty in using the system. STORET has the capability of accessing the Statistical Analysis System (SAS) for statistical analyses.

(2) WATSTORE, developed and operated by the USGS, is available for use by Corps Division and District personnel on an AMDAHL computer, but the USGS is restrictive concerning potential users. Past users of WATSTORE expressed more confidence in data reliability than the users of STORET. The data in WATSTORE are verified and then transferred to permanent storage in WATSTORE and STORET. WATSTORE, like STORET, provides a limited number of statistical analysis packages, but it does provide the user with more advanced graphical techniques.

(3) AURAS, developed by the US Army Engineer Division, Ohio River, resides on the Computer Sciences Corporation INFONET system, which is on a UNIVAC 1108 that is being phased out. However, the AURAS program has been converted to Harris computers. AURAS provides the user with the ability to augment current Corps water quality databases but has limited statistical analysis and graphics or tabular display routines.

(4) The Scientific Information Retrieval System (SIR), developed by SIR, Inc., resides on the Boeing Computer Services CDC 7600 computer. SIR, a more advanced data storage and retrieval system than STORET, WATSTORE, and AURAS, interfaces the user with statistical analysis packages (Statistical Package for the Social Sciences and Biomedical Statistical Package) for analyzing extracted data. SIR does not maintain a nationwide water quality database; however, it does have the necessary language commands for building individual databases. SIR provides the user with good, reliable data storage and retrieval strategies along with a host of analytical capabilities.

(5) UPGRADE was developed and is maintained by the Council on Environmental Quality. The system resides on a commercial computer system and is accessible only by authorized users. UPGRADE has access to a resident water quality database and has an English language prompting command structure. UPGRADE has access to the SAS.

(6) NAWDEX was developed by the USGS and currently resides on the computer system at the USGS National Center in Reston, Virginia. NAWDEX primarily assists users in locating and retrieving information from other databases. Additional capabilities are not part of the software system. However, as a data storage and retrieval system, NAWDEX easily guides users through prompting sessions that allow the creation of or retrieval from the databases.

(7) Of the six systems discussed above, five are Government-sponsored database management systems. The remaining system, SIR, was developed by private enterprise and currently is available through Boeing Computer Services or may be adapted for use on in-house computer facilities. Other data management systems that are available for use include: Integrated Data Management System (IDMS), Information Management System (IMS), Adaptable Database Management System (ADABAS), or TOTAL. Database management systems are continually improving and becoming more user oriented. Periodic reviews of available systems are required.

c. Specific Water Quality Database Management and Analysis Systems. Specific water quality database management systems are characterized by their ability to simplify the database management storage and retrieval strategies. The commercial market for specific water quality database management systems is not as extensive as the general database management systems market. The five major software systems are described in the following paragraphs. All of these systems provide the user with a host of mathematical and statistical analysis routines. Each software package has advantages and disadvantages for particular applications and must be considered on a case-by-case basis.

(1) The Biomedical Statistical Package (BMDP) is marketed by BMDP Statistical Software, Los Angeles, California, and has provided statisticians, engineers, and scientists with a comprehensive and reliable software package for over 22 years. BMDP consists of 40 specialized statistical analysis routines, ranging from basic description statistics to a general linear models program that handles all aspects of unbalanced statistical designs. BMDP does provide for a limited amount of data storage and retrieval but, for large databases, it is better to use BMDP in conjunction with a front-end data storage and retrieval system. Graphics subsystems are not available with the complete BMDP package, while programming within the system is allowed on only a limited basis.

(2) The Statistical Package for the Social Sciences (SPSS), marketed by SPSS, Inc., of Chicago, Illinois, is available in two versions: the batch SPSS version and the conversation SPSS version known as SCSS. Both systems offer the user a wide selection of statistical analysis routines. However, only the SCSS version permits interactive communication between the database and the statistical analysis package. As with the BMDP, SPSS provides limited graphics capabilities, and if communication with a large, complex environmental database is required, a front-end data storage and retrieval system would be needed.

(3) The International Mathematical and Statistical Libraries (IMSL) is marketed by IMSL, Inc., Houston, Texas, and is probably the most complete package related to mathematical and statistical applications. IMSL is a FORTRAN-based system that consists of approximately 500 subroutines within the areas of mathematics and statistics. IMSL provides no interfacing programs between databases and the set of subroutines. A front-end storage and retrieval system, therefore, is mandatory. IMSL provides little or no graphics capabilities.

(4) Minitab, marketed by the Minitab Project at Pennsylvania State University, is the most recent research database management package marketed. Minitab has been customized to be compatible with a wide variety of computer systems, but currently has a limited amount of statistical analysis routines and graphics capabilities. The system is inexpensive and provides the user with easy access commands.

(5) The Statistical Analysis System (SAS), marketed by SAS Institute, Raleigh, North Carolina, is by far the most complete database management system currently marketed. SAS provides a wide range of mathematical and statistical analysis procedures, reliable database management strategies, color graphics, time series algorithms, report writing, operations research, and interface routines that permit interfacing between other mathematical and statistical packages and the IBM database management system known as the Information Management System (IMS). SAS is also programmable. This allows the user to construct mathematical algorithms not included in the basic package and incorporate them as library routines for later reference. SAS has an easy language command set and requires minimal training for the noncomputer-oriented individual. SAS is currently not available on the Harris system; it is available for the IBM and Digital systems.

5-8. Selection Criteria. System selection criteria should concentrate on the end-product user requirements and the available software packages. These software packages should provide the database system strategies, mathematical and statistical algorithms, graphic and tabular display routines, and programming capabilities, as well as compatability with other software packages so that other pertinent analysis packages can be incorporated easily. The system also should have reliable vendor support and be cost effective for the project. The database management system should focus on the needs of the engineer and scientist rather than on the requirements of the software system.

Section IV. Data Presentation

5-9. Methods. For all studies, data portrayal and display are a vital part of the data interpretation. The three methods of presentation most commonly used are: a complete listing of the database in some predetermined order, summary tables, and graphic displays. The complete database listing can be an important part of the data analysis but generally does not contribute significantly to data interpretation. Summary tables and graphic displays should be used; however, it is critical that these summary procedures enhance, not confuse, the water quality information presented.

5-10. Summary Tables. Summary tables should reduce the volume of data into a finite set of statistics, called descriptive statistics, which represent unbiased estimates of the unknown population parameters. Usually these tables consist of average or mean values and standard deviations of the population characteristics being investigated. Although the sample average and standard deviation are unbiased estimators, the complete picture of the underlying probability distribution that generated the measurements may not be adequately represented by only these two estimators. For example, if the probability distribution is symmetrical, then the sample mean, standard deviation, and confidence intervals adequately describe the underlying distribution. However, if the distribution is skewed, these estimators may be biased, and misinterpretations and erroneous conclusions can be drawn. To complement these estimators, such statistics as median, minimum, and maximum values and quartile points representing the 25th and 75th quartiles should also be displayed

(Table 5-4). With these additional statistics, the complete picture of the underlying probability distribution can be given.

5-11. Graphic Displays. Graphic displays complement summary tables. Graphic presentations can highlight areas that might not be detected from summary tables or rigorous statistical analysis of the data. A number of graphic displays that can be used to assess data distributions are discussed below.

a. X-Y Plots. Two-dimensional X-Y plots are the classical approach for graphically displaying the sample average and dispersion ($x \pm \sigma^2$) of population characteristics (Figure 5-2a). This plot displays two important characteristics: how the average value changes over sampling locations or time, and the homogeneity of variance assumptions, which are made in most poststudy analysis procedures. These plots can be improved by plotting not only the averages, but also the overall average with 100 $(1 - \alpha)$ percent confidence bands. (The letter α refers to the probability of error associated with the analytical procedure.) Presenting these features graphically can assist in data interpretation.

b. Quartile Plots. Quartile plots are an enhancement to the X-Y plots discussed above. This plot graphically displays the entire sample in the following manner. For the predetermined order, the maximum and minimum values, along with the 25th, 50th, and 75th quartile points, and the sample average can be plotted with a rectangular box enclosing the 75th and 25th quartile points. The interpretation of this plot can lead to discussion of symmetry and order statistics as they relate to differences among sampling locations or time. An example of this plot is shown in Figure 5-2b. As shown, the averages appear to be fairly uniform; however, skewness of the distributions is noticeable at locations B and C, whereas location A has a fairly symmetrical distribution. Furthermore, the medians (Q_{50}) are considerably different, and 50 percent of the data from location A and approximately 75 percent of the data from C are larger than the 75th quartile point for location B.

c. Tukey's Box Plot. Tukey's box plot resembles the quartile plot, but there are subtle differences between the two. The box plot, as with the quartile plot, will plot Q_{25}, Q_{50}, Q_{75}, and the sample average with a rectangle enclosing the 25th and 75th quartile points (see Figure 5-2c). The central vertical line extends from the box as far as the data extend or to a distance of, at most, 1.5 interquartile range; that is, the interquartile range is the distance between the 25th and 75th quartile points. Any value more extreme than this is marked with "0" if it is within 3 interquartile ranges of the box, or with an asterisk if it is still more extreme. Reference 105 provides more information about this plot.

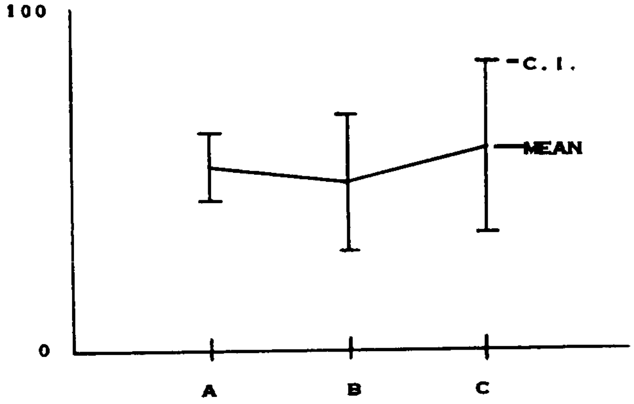
d. Bar Charts. Bar charts (Figure 5-3a) are similar to X-Y plots, when averages are considered. The primary difference between the two is that X-Y plots depict the average as a single point while bar charts represent the average as a rectangular surface that encloses the area between the X-

TABLE 5-4

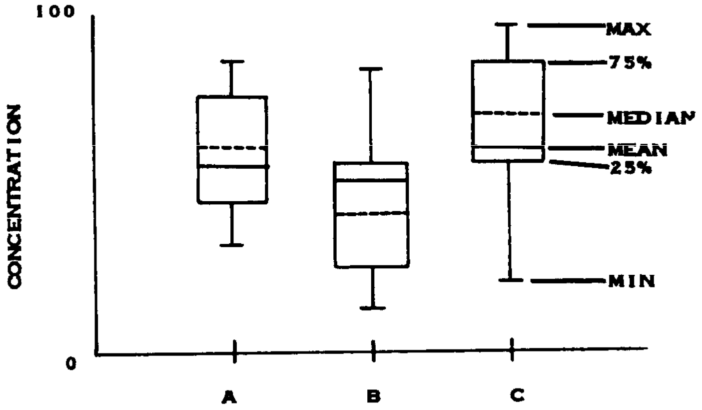
Example of Description Statistics That Can Be Applied to Water Quality Data

```
                    S T A T I S T I C A L   A N A L Y S I S   S Y S T E M
                                        UNIVARIATE
VARIABLE POP                  LABEL 1970 CENSUS POPULATION IN MILLIONS
                                         MOMENTS

           N                      50          SUM WGTS            50
           MEAN               4.0472          SUM             202.36
           STD DEV           4.32932          VARIANCE        18.743
           SKEWNESS          2.05522          KURTOSIS       4.54561
           SS                 1737.4          CSS            918.407
           CV                106.971          STD MEAN      0.612258
           T:MEAN=0          6.61028          PROB>|T|        0.0001
           W:NORMAL         0.763044          PROB<W            0.01

                                        QUARTILES

            100% MAX           19.95              99%         19.095
             75% Q3            4.665              95%         11.495
             50% MED            2.59              90%          10.65
             25% Q1             0.97              10%           0.55
              0% MIN             0.3               5%          0.385
                                                   1%            0.3
             RANGE             19.65
             Q3-Q1             3.695
             MODE               3.92

                                         EXTREMES

               LOWEST     ID                    HIGHEST     ID
                  0.3(ALASKA  )                   11.01(ILL      )
                 0.33(WYO     )                    11.2(TEXAS    )
                 0.44(VT      )                   11.79(PA       )
                 0.49(NEV     )                   18.24(NY       )
                 0.55(DEL     )                   19.95(CALIF    )
```

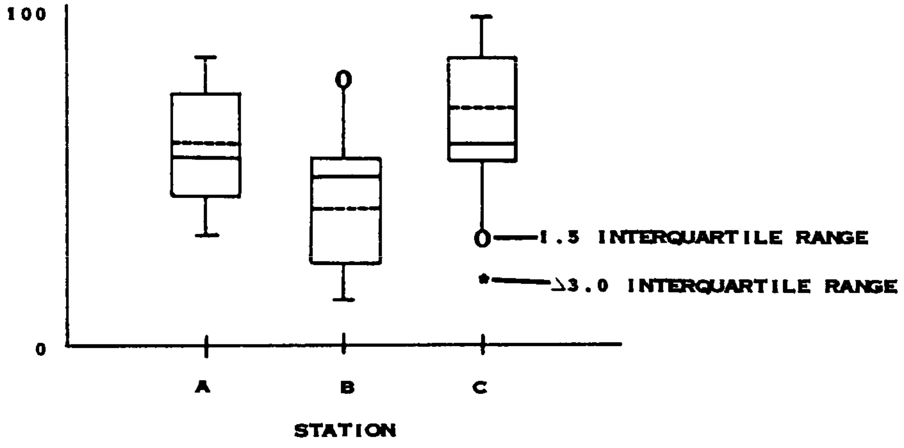
SOURCE: Ref. 96.



a. X-Y plots of mean and confidence intervals (C.I.)



b. Box plot with mean, median, and quartiles



c. Tukey's box plot with interquartile range

Figure 5-2. Example data plots

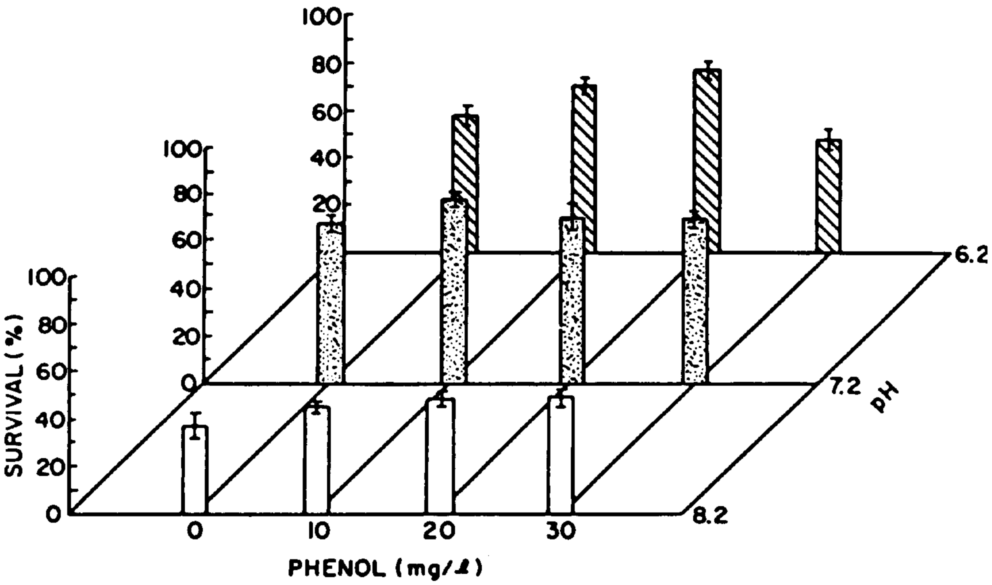
the average value. Although this figure may look very similar to a histogram, the two should not be confused, especially when the average value is being represented by the bar chart. Histograms have a continuous X-axis and the height of the bars represents frequency (Figure 5-3b). Although the bar chart is used primarily to plot average concentrations, it can and has been successfully used to display total values, frequency, percentages, etc. It is a flexible plot and can be easily extended to three dimensions.

e. Scatter Diagrams. Scatter diagrams are used to display relationships between two population characteristics, such as specific conductivity and time, TDS and specific conductivity, and total phosphorus and suspended solids (Figure 5-4). While these diagrams show trends and possible correlations, the appropriate statistical analysis should be performed prior to making inferences about the relationship between characteristics.

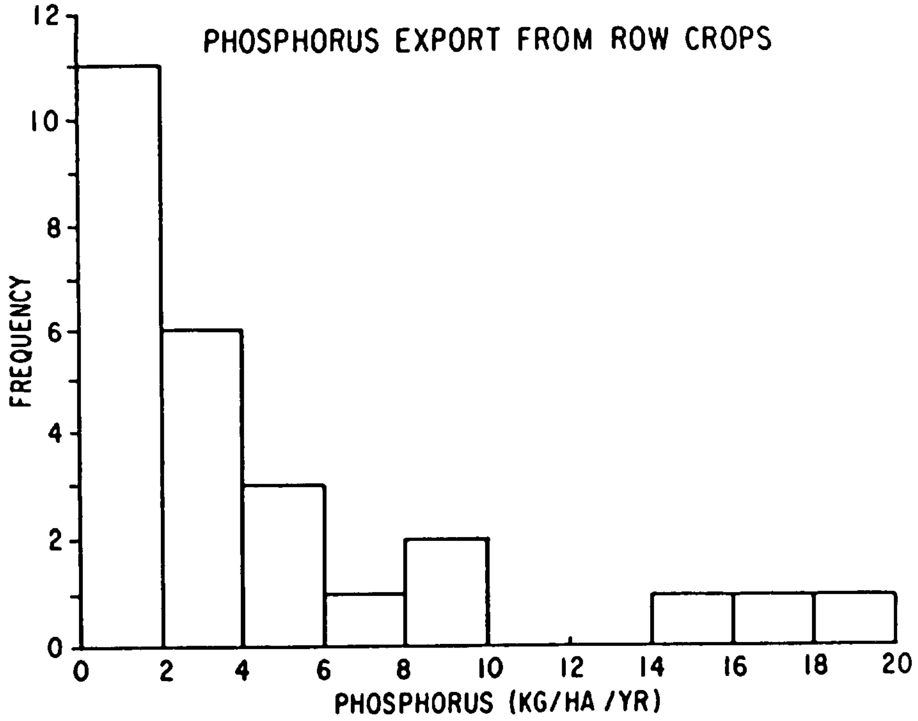
f. Annual Summary. At a minimum, inflow and outflow constituents should be plotted versus time on an annual basis. Water quality constituents collected at inpool stations should be plotted versus depth for each sampling date. Water quality constituents can be compared among years easily and quickly with graphic displays. Specialized annual summaries of reservoir constituents such as vertical (depth-time) and horizontal (depth-distance) isopleth diagrams can provide useful visual summaries for data presentation.

5-12. Quality Assurance. Quality assurance procedures are important not only for field sampling and laboratory analyses, but also for database management. Database entries should also be subjected to rigorous QA procedures so that aberrant and/or erroneous values can be removed or modified. Screening programs can be used to detect gross errors (e.g., transposition of pH value of 7.1 to 1.7); however, subtle errors such as pH 6.7 instead of 7.6 must be verified manually by comparing individual values. An error-free database is absolutely essential if valid scientific and statistical conclusions are to be derived.

5-13. Statistical Analysis. The use of appropriate statistical methods is essential for proper analysis and interpretation of reservoir water quality data and should be an integral part of the sampling program. Generally, this requires discussions with a statistician before the analyses are performed to minimize time and costs associated with the analyses. Statistical analyses should be performed only when all quality assurance checks have been satisfied, erroneous data entries have been removed, and the data have been graphically displayed. Statistical treatment of the data must be based on the sampling design and the assumptions made about the population characteristics under investigation. Statistical analyses are of two general types: parametric and nonparametric. Assumptions about the underlying probability distribution determine the appropriate statistical analyses. Before performing other statistical analyses, however, preliminary characteristics of the data can be determined by using descriptive statistics.

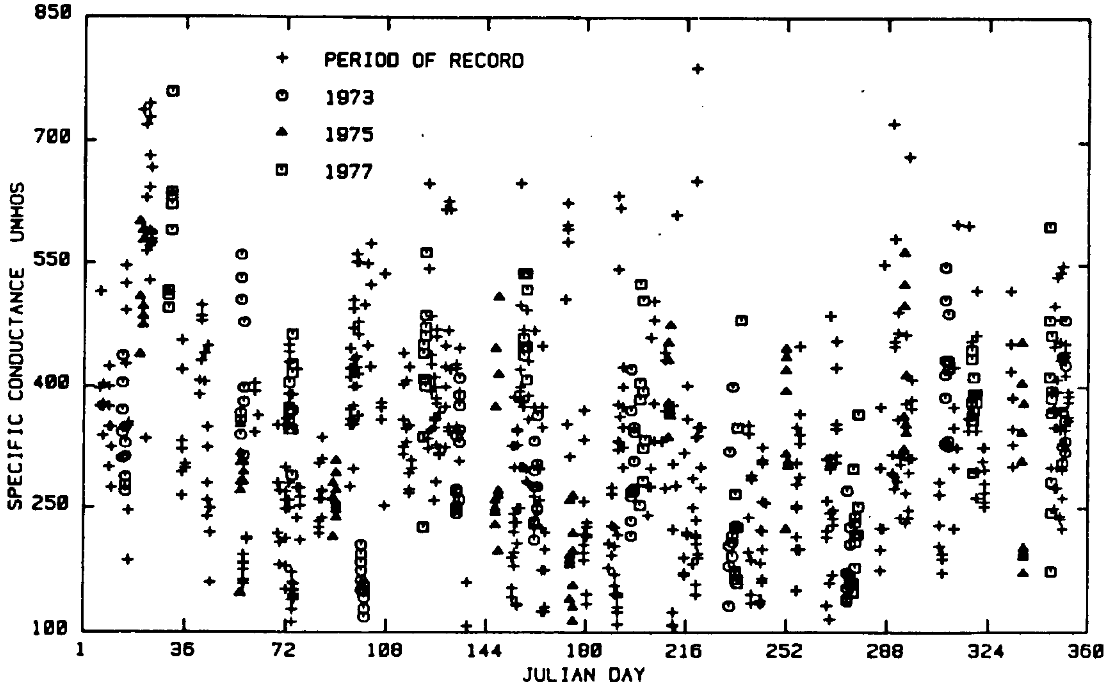


a. Sample bar chart

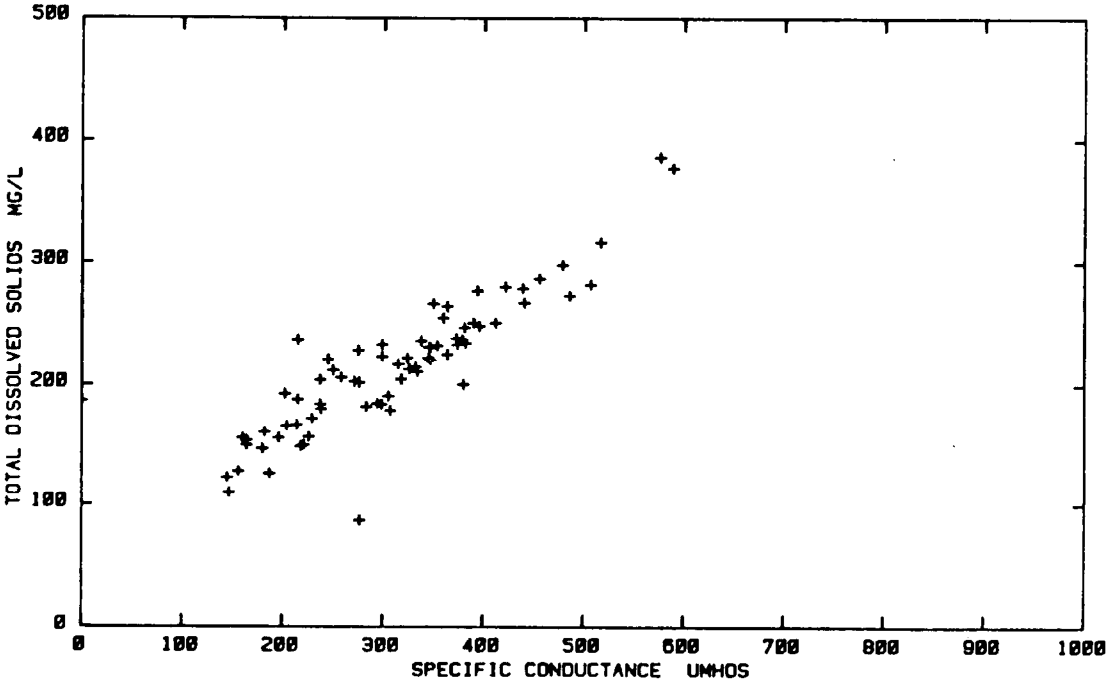


b. Sample histogram

Figure 5-3. Comparison of graphic display methods



a. Specific conductance versus time



b. TDS versus specific conductance

Figure 5-4. Example scatter diagrams

a. Descriptive Statistics. Descriptive statistics usually summarize or characterize a data set (Table 5-4). No assumptions about the probability distribution are made or implied for descriptive statistics. The characteristics may be a mean, median, mode, variance, range, etc. Each estimator summarizes a data set in a unique way and represents a specific population characteristic. For example, the mean is the arithmetic average of n sample values, while the median represents the middle value of n measurements. The mode is defined as the measurement with the maximum frequency. These characteristics provide information on the sample population. The mean and median are similar, for example, if the distribution of values is symmetrical but will diverge as the distribution becomes skewed. The mean is more influenced by outliers than the median. Quantitative measures of the data distribution such as the range, variance, or standard deviation provide information on the dispersion of the data. Descriptive statistics should be computed as part of the initial data evaluation. Additional information can be found in Snedecor and Cochran (Ref. 99) or Steel and Torrie (Ref. 101).

b. Parametric Statistics. Parametric statistical inferences about a finite number of unknown population parameters are based on an underlying density or probability function such as the normal distribution, binomial distribution, Poisson distribution, etc. Since all measurements are subject to error, the usual assumption is that these measurement errors have an underlying normal distribution with a zero mean and an unknown variance. The error terms are assumed to be independent, identically distributed, generally with a normal distribution (i.e., homogeneity of variances), and additive. The significance of these assumptions is discussed in Snedecor and Cochran (Ref. 99), Sokal and Rohlf (Ref. 100), and Steel and Torrie (Ref. 101). These assumptions can be represented by the linear model

$$Y_i = \mu + \varepsilon_i$$

where

Y_i = measurement made on the i^{th} sample ($i = 1,2...n$)

μ = population mean of the measurements

ε_i = the error involved in making the i^{th} measurement (i.e., the deviation of the i^{th} measurement from the unknown population mean)

With this as the underlying model and the above assumptions, the measurement Y_i will possess a normal distribution with mean μ and variance σ^2.

(1) Statistical inference. When sample characteristics are used to infer some information about the general population, the subject is called inductive statistics or statistical inference. Inference becomes a scientific method, differentiating it from mere guessing, when probability statements concerning the accuracy of the estimate or reliability of a decision are

incorporated. The two types of problems most frequently encountered are estimation and test of hypotheses.

(a) Estimation. The area of estimation considers questions such as: what are the estimates of the unknown population parameters based on the sample measurements, and what properties do these estimators exhibit? The class of estimators may be divided into two areas: point estimates and interval estimates. The usual estimators are the sample average and variance, which estimate the population mean and variance, respectively, and can either be reported as point estimates or interval estimates. The interval estimate for the mean is the 100 $(1 - \alpha)$ percent Student confidence interval, while the 100 $(1 - \alpha)$ percent confidence interval for the population variance is based on the Chi-square distribution. The symbol α represents the probability of rejecting the hypothesis when this hypothesis is true in favor of an alternative hypothesis that is false. This level has typically been $\alpha = 0.05$ but can be set at any level, i.e., 0.20 or 0.01. Interval estimates can be extended to the two-sample case, i.e., paired samples or independent samples. (Further information is given in Refs. 99 and 101.) Population parameters can be estimated in three ways: maximum likelihood techniques, least squares techniques, and the method of moments. With the assumption of normality, these estimation methods produce similar results. However, if the normality assumption is violated, the estimates may vary considerably. In order to determine which estimator is best, three properties of estimators should be considered: bias, consistency, and minimum variance. For more information on these techniques and properties, see Mood and Graybill (Ref. 88), Hogg and Craig (Ref. 76), or Kendall and Stuart (Ref. 83).

(b) Test of hypotheses. The test of hypotheses is an extension of interval estimation. Confidence intervals usually concentrate on one or two sample procedures, while hypothesis testing extends this concept to multiple samples. The underlying goal of hypothesis testing is to assist in making decisions about differences among population characteristics. Statistical analysis only assists in the decision process, however. Statistics is a tool that must be used with good engineering and scientific judgment in making decisions about population characteristics. One- and two-sample tests, the most elementary form of hypothesis testing, involve decisionmaking about population parameters that characterize either one or two populations. Decisions can be made on a population mean, differences in population means, effects of treatments on a population mean, a population variance, or homogeneity of population variances. Statistical tests appropriate for decisionmaking about each of these areas are: the one-sample t-test, the two-sample independent t-test, the paired t-test, the Chi-square test, and the F-test, respectively. Several of these tests are summarized in Table 5-5, and explanations are given in Snedecor and Cochran (Ref. 99), Sokal and Rohf (Ref. 100), and Steel and Torrie (Ref. 101). When the statistical problem involves two or more factors, the appropriate statistical test is the analysis of variance (ANOVA). Essentially, the ANOVA partitions the total variance into known sources of variation. From here, significant and nonsignificant contributions to the total variance can be observed. For example, in investigating the effects of a

TABLE 5-5

Summary of Parametric Statistical Tests

	Two-Sample			Measures of Association
One-Sample	Paired Samples	Independent Sample	k-Sample	
A. Student's t-test Assumptions: 1. Normal distribution 2. Unknown variance	A. Paired t-test Assumptions: 1. Normality 2. Unknown variance KEY: Two experiments performed on one sampling unit. 3. Hypothesis $H_o: \mu = 0$	A. Independent E-test Assumptions: 1. Normality 2. Unknown, but common variances KEY: Independent sampling units. 3. Hypothesis $H_o: \mu_1 = \mu_2$ B. F-test Assumptions: Normality KEY: Test hypothesis of equal variances.	A. One-way ANOVA B. Randomized Complete Block C. Factorials D. Nested Designs E. Nested Factorials F. Randomized Incomplete Block Design Assumptions: 1. Normality 2. Equal variances 3. Additive error term Transformations: 1. Logarithmic 2. Square root 3. Arcsine	A. Linear Correlation B. Linear Regression C. Nonlinear Regression D. Time Series E. Analysis of Covariance F. Response Surface Models

hydropower reservoir on a river, the design could be to establish river stations above and below the hydropower reservoir in the main channel and along the banks and to collect both surface and bottom samples. The sampling units are subjected to outside sources of variations. Such sources could be treatment or factor effects due to the lack of homogeneity among sampling units. These outside sources of variation can be identified and explained by partitioning the total variance into the variance attributable to each of these outside influences, such as main channel and bank locations or above- and below-reservoir responses. An F-test, which is a test for the equality of two variances, can be constructed so that significance or nonsignificance of each of these factors can be determined. For the significant effects, post-ANOVA procedures can be used to separate the treatment effects such as main channel versus bank locations. More detailed information concerning the ANOVA, post-ANOVA tests, and transformation of data to satisfy the normality assumption is given in Refs. 99 and 101. General characteristics are summarized in Table 5-5.

(2) Regression analysis.

(a) Regression analysis is divided into two categories: cause-and-effect models and correlation and regression models. The primary distinction between these two categories is the assumptions placed on the measured variables. With cause-and-effect models, the relationships between a dependent response variable and a set of independent variables are studied. These models assume the independent variable (i.e., X variable) is fixed or measured without error. This means only the dependent variable (i.e., Y variable) is a random variable and includes random error. Usually, the models are defined as a polynomial relationship between the independent and dependent variables. Multiple linear relationships also can be defined, as long as the assumption of fixed independent variables is preserved. Some typical cause-and-effect relations are:

$$Y = \sum_{i=0}^{p} \alpha_i X^i \qquad \text{(general polynomial model)}$$

$$Y = \exp\left(\sum_{i=0}^{p} \alpha_i X^i\right) \qquad \text{(general exponential model)}$$

$$Y = \sum_{i=0}^{p} \alpha_i X_i \qquad \text{(general multiple linear model)}$$

where

α_i = unknown parameters

X^i = an independent variable raised to the i^{th} power

X_i = the i^{th} independent variable

(b) The estimation technique used for providing estimators of the unknown α_i values is the least squares technique. Correlation and regression models do not adhere to the assumption of fixed independent variables. With this type of condition, several characteristics about the population are measured from the same sample unit. For example, assume temperature, suspended solids, DO, Fe, Mn, and H_2O measurements are made on water samples. The aim is to investigate the multivariate relationship among these variables. The procedure, which provides an interdependent structure among these measurements, is correlation and regression. The regression model is usually a multiple linear model, and the regression parameters α_i are estimated by the least squares technique. The subtle differences between these two types of regression problems are the estimation of error variance and the measure of goodness of fit. With the cause-and-effect model, the error variance estimate can be obtained from the ANOVA table while partial correlation and variance estimates have to be computed separately with the correlation and regression model. With the cause-and-effect model, the coefficient of determination R^2 is used to discuss the percent of the total variance explained by the model, while the sample correlation coefficients and partial correlation coefficients are used to discuss significant relationships in correlation and regression models. Other measures of association are listed in Table 5-5. A more complete discussion of this subject is found in Drapier and Smith (Ref. 63), Snedecor and Cochran (Ref. 99), and Steel and Torrie (Ref. 101).

(3) Time-series. Observations on a population characteristic through time generate an ordered set of data known as a time series. The values assumed by a variable at time t may or may not embody an element of random variation but, in a majority of the cases, random variation will be present. Time-series analysis can be used to investigate: a trend, or long-term movement; oscillations about the trend of greater or less regularity; a seasonal effect; and a random, unsystematic, or irregular component. Time-series analysis assumes data were collected at regular intervals (i.e., daily, weekly, or 30-day) and generally requires relatively long records. A more complete discussion of time-series analysis can be found in Box and Jenkins (Ref. 54) or Kendall and Stuart (Ref. 83).

c. Nonparametric Statistics. The classical approach to data analysis is parametric statistics. However, there are alternative procedures called distribution-free inference, which are as reliable and robust as the classical parametric procedures. The complete area of distribution-free inference is known as nonparametric statistics. In a distribution-free inference, for testing or estimation, assumptions regarding the specific underlying population distribution are not necessary. The term nonparametric test implies a test for a hypothesis that is not a statement about population parameter values, such as the mean and variance. The type of hypothesis, then, considers only the form of the population, as in goodness-of-fit tests, or some characteristic of the probability distribution of the sampled data, as in tests for randomness and trend. Distribution-free test and nonparametric test are not synonymous labels, since distribution-free test relates to the distribution of the test statistic while the nonparametric test refers to the type of hypothesis being tested. Many parametric tests have nonparametric or distribution-free equivalences (Table 5-6). A complete discussion may be found in Gibbons (Ref. 68) and Siegel (Ref. 98). The following paragraphs introduce some of these procedures.

(1) Tests on goodness of fit. An important problem in statistics relates to obtaining information about the form of the population from which the sample is drawn. For example, the traditional parametric test, based on Student's t-distribution, is derived under the assumption of a normal population. The exact distribution theory and probabilities of making Type I and Type II errors depend on this population form (i.e., Type I = rejecting a hypothesis when it is true; Type II = accepting a hypothesis when it is false). Therefore, it might be desirable to check the reasonableness of the normal assumption before forming any conclusions based on the t-distribution. Tests based on the distribution inference are called goodness-of-fit (GOF) tests. Since a Chi-square distribution can be generated from a population of standard normal deviates, a Chi-square test can be used to compare the cumulative distribution of the sample population with a Chi-square distribution. The Kolmogorov-Smirnov one-sample test is another nonparametric test that is applicable to continuous frequency distributions. In many cases, it has greater power than the Chi-square test for GOF. Additional information can be found in Gibbons (Ref. 68), Snedecor and Cochran (Ref. 99), and Sokal and Rohlf (Ref. 100).

(2) General two-sample problem. The analogous parametric problem to the nonparametric two-sample problem is the independent t-test. The t-test checks for equality of means under the assumption of normality and homogeneous variances while the nonparametric tests emphasize differences in location, scale, and medians. Some of the more common tests are the Wald-Wolfowitz runs test, the Kolmorgorov-Smirnov two-sample test, the median test, and the Mann-Whitney U-test (see Refs. 68 and 98; Table 5-6).

(3) Test of equality of k independent samples. Extensions of the two-sample tests are available in nonparametric statistics similar to procedures. Some applicable nonparametric tests for comparing k-samples are: the k-sample median test, the Kruskal-Wallis one-way ANOVA test, the Friedman two-way ANOVA test by ranks, and Conover's k-sample slippage test (Ref. 60).

(4) Measures of association for bivariate samples. There are equivalent nonparametric tests to measure the association between variables analogous to

TABLE 5-6

Summary of Nonparametric Statistical Tests

Level of Measurement	One-Sample Case	Two-Sample Case		k-Sample Case		Measure of Correlation
		Related Samples	Independent Samples	Related Samples	Independent Samples	
Nominal[1]	Binomial test	McNemar test for the significance of changes	Fisher exact probability test	Cochran Q test	Chi-square test for k independent samples	Contingency coefficient
	Chi-square test		Chi-square test for two independent samples			
Ordinal[2]	Kolmogorov-Smirnov one-sample test	Sign test	Median test	Friedman two-way analysis of variance	Extension of median test	Spearman rank correlation
		Wilcoxon matched pairs signed-rank	Mann-Whitney *U* Test		Kruskal-Wallis one-way analysis of variance	Kendall rank correlation
	One-sample runs test		Kolmogorov-Smirnoff two-sample test			Kendall partial rank correlation coefficient
			Wald-Wolfowitz runs test			Kendall coefficient of concordance

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[1] When numbers of other symbols are used to classify a characteristic of a population, but the order of magnitude has no bearing on the outcomes of the classification scheme: arbitrary scale.

[2] When numbers or other symbols are used to classify a characteristic of a population and the order of magnitude implies a mathematical relationship.

parametric measures of association or correlation. These measures are Kendall's tau coefficient and Spearman's coefficient of rank correlation (Table 5-6). These measures of association are as powerful as the classical approach to correlation (e.g., the Pearson product-moment correlation coefficient) and are more easily computed. Gibbons (Ref. 68) and Siegel (Ref. 98) provide information on these techniques.

d. Discussion. This section has briefly discussed some essential components of statistical analysis, including both parametric and nonparametric analyses. Parametric statistics rely on certain assumptions about the underlying probability distribution and concentrate in the areas of estimation and hypothesis testing about the unknown population parameters. Nonparametric procedures make no assumptions about the distributional properties of the population and allow for broader hypotheses or inferences to be examined. Each area, parametric and nonparametric, can provide the engineer and scientist with valid and reliable results. Within each area, the appropriate statistical tests are ultimately based on the study objectives and sampling program design.

APPENDIX A
REFERENCES

Department of the Army, Corps of Engineers*

1. ER 1110-2-1402, "Hydrologic Investigation Requirements for Water Quality Control."

2. ER 1130-2-334, "Reporting of Water Quality Management Activities at Corps Civil Works Projects."

3. ER 1130-2-415, "Water Quality Data Collection, Interpretation and Application Activities."

4. EP 70-1-1, "Remote Sensing Applications Guide."

5. EP 1165-2-1, "Digest of Water Resources Policies and Authorities."

Department of the Army, Corps of Engineers, Waterways Experiment Station**

6. Barko, J. W., R. M. Smart, M. S. Matthews, and D. G. Hardin. 1979. "Plant-Mediated Phosphorus Mobilization from Sediments: Potential Influence on Freshwater Phosphorus Cycling," Technical Report E-79-3.

7. Bohan, J. P., and J. L. Grace, Jr. 1973. "Selective Withdrawal from Man-Made Lakes: Hydraulic Laboratory Investigation," Technical Report H-73-4.

8. Buchak, E. M., and J. E. Edinger. 1982. "User Guide for LARM2: A Longitudinal-Vertical Time-Varying Hydrodynamic Reservoir Model," Instruction Report E-82-3.

9. Burton, G. A., Jr. 1982. "Microbiological Water Quality of Impoundments: A Literature Review," Miscellaneous Paper E-82-6.

10. Environmental Laboratory. 1986 (Jul). "CE-QUAL-R1: A Numerical One-Dimensional Model of Reservoir Water Quality; User's Manual," Instruction Report E-82-1 (Revised Edition, supersedes December 1982 version).

11. Ford, D. E., and L. S. Johnson. 1986. "An Assessment of Reservoir Mixing Processes," Technical Report E-86-7.

---

* Available from: Corps of Engineers Publication Depot, 890 South Pickett St., Alexandria, VA 22304.

** Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

12. Ford, D. E., and M. C. Johnson. 1983. "An Assessment of Reservoir Density Currents and Inflow Processes," Technical Report E-83-7.

13. Gunnison, D. 1982. "Reservoir Site Preparation--An Update," Environmental and Water Quality Operational Studies, Vol E-82-5 (Jul).

14. Gunnison, D., J. M. Brannon, R. L. Chen, I. Smith, Jr., and T. C. Sturgis. 1984. "Richard B. Russell Dam and Reservoir: Potential Water Quality Effects of Initial Filling and Decomposition of Vegetation," Miscellaneous Paper E-84-2.

15. Gunnison, D., J. M. Brannon, I. Smith, Jr., G. A. Burton, and P. L. Butler. 1979. "Water Quality Evaluation of Proposed Twin Valley Lake, Wild Rice River, Minnesota; Appendix B: A Determination of Potential Water Quality Changes in the Hypolimnion During the Initial Impoundment of the Proposed Twin Valley Lake," Technical Report EL-79-5.

16. Johnson, B. H. 1981. "A Review of Numerical Reservoir Hydrodynamic Modeling," Technical Report E-81-2.

17. Matter, W., P. Hudson, J. Nestler, and G. Saul. 1983. "Movement, Transport, and Scour of Particulate Organic Matter and Aquatic Invertebrates Downstream from a Peaking Hydropower Project," Technical Report E-83-12.

18. McCutcheon, S. C. 1983. "Evaluation of Selected One-Dimensional Stream Water-Quality Models with Field Data," Technical Report E-83-11.

19. Peddicord, R. M., ed. 1984. "Guidance for Contracting Biological and Chemical Evaluations of Dredged Material," Technical Report in preparation.

20. Plumb, R. H., Jr. 1982. "Procedures for Handling and Chemical Analysis of Sediment and Water Samples," TR EPA/CE-81-1, US Environmental Protection Agency and US Army Engineer Technical Committee on Criteria for Dredged and Fill Material.

21. Roberts, P. J. W. 1981. "Jet Entrainment in Pumped-Storage Reservoirs," Technical Report E-81-3.

22. Smith, D. R., Wilhelms, S. C., Holland, J. P., Dortch, M. S., and Davis, J. E. 1986. "Improved Description of Selective Withdrawal Through Point Sinks," Technical Report in preparation.

23. Thompson, J. F. 1983. "A Boundary-Fitted Coordinate Code for General Two-Dimensional Regions with Obstacles and Boundary Intrusions," Technical Report E-83-8.

24. US Environmental Protection Agency and US Army Engineer Technical Committee on Criteria for Dredged and Fill Material. 1977 (Jul) (2d printing,

Apr 78). "Ecological Evaluation of Proposed Discharge of Dredged Material into Ocean Waters: Implementation Manual for Section 103 of Public Law 92-532 (Marine Protection, Research, and Sanctuaries Act of 1972)."

25. Walburg, C. H., J. F. Novotny, K. E. Jacobs, and W. D. Swink. 1983. "Effects of Reservoir Releases on Water Quality, Macroinvertebrates, and Fish in Tailwaters: Field Study Results," Technical Report E-83-6.

26. Walburg, C. H., J. F. Novotny, K. E. Jacobs, W. D. Swink, and T. M. Campbell. 1981. "Water Quality, Macroinvertebrates, and Fisheries in Tailwaters and Related Streams: An Annotated Bibliography," Technical Report E-81-8.

27. Walburg, C. H., J. F. Novotny, K. E. Jacobs, W. D. Swink, T. M. Campbell, J. M. Nestler, and G. E. Saul. 1981. "Effects of Reservoir Releases on Tailwater Ecology: A Literature Review," Technical Report E-81-12.

28. Walker, W. W. 1982. "Empirical Methods for Predicting Eutrophication in Impoundments, Phase II: Model Testing," Technical Report E-81-9, Report 2.

29. __________. 1984. "Empirical Methods for Predicting Eutrophication in Impoundments, Phase II: Model Refinements," Technical Report E-81-9, Report 3.

Other Government Publications

30. Driscoll, E. D., J. L. Mancini, and P. A. Mangarello. 1981. "Technical Guidance Manual for Performing Wasteload Allocation; Book II, Streams and Rivers; Chapter 1, Biochemical Oxygen Demand/Dissolved Oxygen and Ammonia Toxicity," Office of Water Regulations and Standards, US Environmental Protection Agency, 401 M St., SW, Washington, DC 20460.

31. Harleman, D. R. F., J. E. Dailey, T. O. Thatcher, D. N. Brocard, and R. A. Ferrara. 1977. "User's Manual for the M.I.T. Transient Water Quality Network Model," EPA-600/3-77-010, US Environmental Protection Agency, 200 Southwest 35th St., Corvallis, OR 97330.

32. Mueller, D. K., D. C. Croft, R. L. George, P. L. Johnson, and R. A. Roline. 1981. "Guidelines for Studies of Potential Eutrophication," Water Quality Planning Technical Memorandum, Bureau of Reclamation, US Department of the Interior, 18th and C Streets, NW, Washington, DC 20240.

33. Norton, W. R. 1978. "Operating Instructions for the Computer Program RMA-7," US Army Engineer Hydrologic Engineering Center, 609 2d St., Davis, CA 95616.

34. Omernik, J. M. 1977. "Nonpoint Source-Stream Nutrient Level Relationships: A Nationwide Study," EPA-600/3-77-105, US Environmental Protection Agency, 200 Southwest 35th St., Corvallis, OR 97330.

35. Orlob, G. T. 1977. "Mathematical Modeling of Surface Water Impoundments, Vol I, Project T-0006 Report," Office of Water Research and Technology, US Department of the Interior, Washington, DC 20240.

36. Roesner, L. A., P. R. Giguere, and D. E. Evenson. 1977. "User's Manual for Stream Water Quality Model (QUAL-II)," EPA Center for Water Quality Modeling, Environmental Research Laboratory, Athens, Ga. Available from US Environmental Protection Agency, 401 M St., SW, Washington, DC 20460.

37. US Army Engineer Hydrologic Engineering Center. 1980. "HEC-5Q Simulation of Flood Control and Conservation Systems (Including Water Quality Analysis)," Draft User Manual, 609 2d St., Davis, CA 95616.

38. __________. 1981. "Water-Quality for River-Reservoir Systems," Draft User Manual, 609 2d St., Davis, CA 95616.

39. US Environmental Protection Agency. 1974. "Biological Field and Laboratory Methods for Measuring the Quality of Surface Waters and Effluents," C. I. Weber, ed., EPA-670/4-73-001, 401 M St., SW, Washington, DC 20460.

40. __________. 1975. "Recommended Design of Sample Intake Systems for Automatic Instrumentation," EPA-600/4-75-012, Environmental Monitoring and Support Laboratory, 26 W St. Clair St., Cincinnati, OH 45268.

41. __________. 1976. "Handbook for Sampling and Sample Preservation of Water/Wastewaters," EPA-600/4-76-049, Environmental Monitoring and Support Laboratory, 26 W St. Clair St., Cincinnati, OH 45268.

42. __________. 1978. "Procedure for the Evaluation of Environmental Monitoring Laboratories," EPA-600/4-78-017, Environmental Monitoring and Support Laboratory, 26 W St. Clair St., Cincinnati, OH 45268.

43. __________. 1979. "Methods for Chemical Analysis of Water and Wastes," EPA-600/4-79-020, Environmental Monitoring and Support Laboratory, 26 W St. Clair St., Cincinnati, OH 45268.

44. __________. 1981. "Clean Lakes Guidance Manual," EPA-440/5-81-003, Office of Water Regulations and Standards, 401 M St., SW, Washington, DC 20460.

45. __________. 1983. "Lake Restoration, Protection and Management," EPA-440/5-83-001, Office of Water Regulations and Standards, 401 M St., SW, Washington, DC 20460.

46. US Geological Survey. 1977. "National Handbook of Recommended Methods for Water-Data Acquisition," Office of Water Data Coordination, 12201 Sunrise Valley Drive, Reston, VA 22092.

47. __________. 1982. "National Water Data Exchange (NAWDEX)," USGS Open-File Report 82-115, Office of Water Data Coordination, 12201 Sunrise Valley Drive, Reston, VA 22092.

Nongovernment Publications

48. American Public Health Association. 1980. Standard Methods for the Examination of Water and Wastewater, 15th ed. Available from: APHA. 1740 Broadway, New York, NY 10019.

49. American Society of Civil Engineers. 1982. "Hydraulic Models," Manual of Engineering Practice No. 25. Available from: United Engineering Center, 345 E 47th St., New York, NY 10017.

50. American Society for Testing and Materials. 1982. "Aquatic Toxicology and Hazard Assessment," ASTM-STP 737, D. R. Branson and K. L. Dickson, eds. Available from: ASTM, 1916 Race St., Philadelphia, PA 19103.

51. Basta, D. J., and B. T. Bowers, eds. 1982. "Analyzing National Systems: Analysis for Regional Residuals - Environmental Quality Management." Available from: Resources for the Future, 1755 Massachusetts Ave., Washington, DC 20036.

52. Bedford, K. W., R. M. Sykes, and C. Libicki. 1983. "Dynamic Advective Water Quality Model for River," Journal of the Environmental Engineering Division, American Society of Civil Engineers, Vol 109, No. 3, pp 535-554. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

53. Box, G. E. P., W. G. Hunter, and W. J. Hunter. 1978. Statistics for Experimenters, John Wiley and Sons, Inc. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

54. Box, G. E. P., and G. M. Jenkins. 1977. Time Series Analysis Forecasting and Control, Holden-Day. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

55. Boyce, F. M. 1974. "Some Aspects of Great Lakes Physics of Importance to Biological and Chemical Processes," Journal of the Fisheries Research Board of Canada, Vol 31, No. 5. Available from: National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

56. Carmack, E. C., and Gray, C. B. J. 1982. "Patterns of Circulation and Nutrient Supply in a Medium Residence-Time Reservoir, Kootenay Lake, British Columbia," Canadian Water Resources Journal, Vol 7, No. 1, pp 51-70. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

57. Carstens, T., and McClimans, T., eds. 1980. Proceedings of the Second International Symposium on Stratified Flow, International Association for Hydraulic Research, TAPIR Publishers. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

58. Cassidy, R. A., D. W. Larson, and M. T. Putney. 1981. "Physicochemical Limnology of a New Reservoir," ASCE Proceedings, Symposium on Surface Water Impoundments, Vol II, pp 1465-1473. Available from: American Society of Civil Engineers, 345 E 47th St., New York, NY 10017.

59. Chow, V. T., ed. 1964. Handbook of Applied Hydrology, McGraw-Hill. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

60. Conover, W. J. 1968. "Two k-Sample Slippage Tests," American Statistical Association Journal, Vol 63, pp 614-626. Available from: National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

61. Croley, T. E., II. 1979. "Hydrologic Computations." Available from: Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, IA 52242.

62. Davis, C. V., and K. E. Sorensen, eds. 1969. Handbook of Applied Hydraulics, 3d ed., McGraw-Hill. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

63. Drapier, N., and H. Smith. 1966. Applied Regression Analysis. Available from: John Wiley and Sons, Inc., Third Ave., New York, NY 10158.

64. Ellis, J. C., and R. F. Lacey. 1980. "Sampling: Defining the Task and Planning the Scheme," Water Pollution Control, Vol 79, No. 4, pp 452-467. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

65. Engler, R. M. 1977. "Contracting for Water Quality Data," Proceedings, Seminar on Water Quality Data Collection and Management, January 1977, Committee on Water Quality, Denver, Colo. Available from: Water Control Branch, Engineering Division, Office, Chief of Engineers, US Army, Washington, DC 20314-1000.

66. Fisher, H. B., E. J. List, R. C. Y. Koh, J. Imberger, and N. H. Brooks. 1979. Mixing in Inland and Coastal Waters. Available from: Academic Press, 111 Fifth Ave., New York, NY 10003.

67. Ford, D. E., and M. C. Johnson. 1981. "Field Observations of Density Currents in Impoundments," ASCE Proceedings, Symposium on Surface Water Impoundments, Vol II, pp 1239-1248. Available from: American Society of Civil Engineers, 345 E 47th St., New York, NY 10017.

68. Gibbons, J. D. 1971. Nonparametric Statistical Inference. Available from: McGraw-Hill Book Co., 1221 Ave. of the Americas, New York, NY 10020.

69. Green, R. H. 1979. Sampling Design and Statistical Methods for Environmental Biologists, John Wiley and Sons, Inc. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

70. Gunnison, D., J. M. Brannon, I. Smith, Jr., G. A. Burton, and K. M. Preston. 1980. "A Reaction Chamber for Study of Interactions Between Sediments and Water Under Conditions of Static or Continuous Flow," Water Research, Vol 14, pp 1529-1532. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

71. Gunnison, D., R. L. Chen, and J. M. Brannon. 1983. "Relationship of Materials in Flooded Soils and Sediments to the Water Quality of Reservoirs; I. Oxygen Consumption Rates," Water Research, Vol 17. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

72. Hakanson, L. 1982. "Lake Bottom Dynamics and Morphometry: The Dynamic Ratio," Water Resources Research, Vol 18, No. 5, pp 1444-1450. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

73. Hansen, N. O. 1978. "Mixing Processes in Lakes," Nordic Hydrology, Vol 9, pp 57-74. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

74. Henderson, F. 1966. Open Channel Flow, Macmillan Publishers. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

75. Hildebrand, S. G., ed. 1980. "Analysis of Environmental Issues Related to Small-Scale Hydroelectric Development; III. Water Level Fluctuation," Environmental Sciences Division Publication 1591 (ORNL/TM-453). Available from: Oak Ridge Natl. Laboratory, PO Box P, Oak Ridge, TN 37830.

76. Hogg, R. V., and A. T. Craig. 1978. Introduction to Mathematical Statistics, 4th ed., Macmillan Publishers. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

77. Hutchinson, G. E. 1957. A Treatise on Limnology; I. Geography, Physics, and Chemistry, John Wiley and Sons, Inc. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

78. __________. 1967. A Treatise on Limnology; II. Introduction to Lake Biology and the Limnoplankton, John Wiley and Sons, Inc. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

79. Imberger, J. 1979. "Mixing in Reservoirs," Mixing in Inland and Coastal Waters. Available from: Academic Press, Inc., 111 Fifth Ave., New York, NY 10003.

80. __________. 1980. "Selective Withdrawal: A Review," Proceedings of the Second International Symposium on Stratified Flow, Trondheim, Norway, International Association for Hydraulic Research, T. Carstens and T. McClimans, eds., TAPIR Publishers. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

81. Imberger, J., and P. F. Hamblin. 1982. "Dynamics of Lakes, Reservoirs, and Cooling Ponds," Annual Review of Fluid Mechanics, Vol 14, pp 153-187. Available from: National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

82. Johnson, M. C., D. E. Ford, E. M. Buchak, and J. E. Edinger. 1981. "Analyzing Storm Event Data from DeGray Lake, Arkansas, Using LARM," paper presented at 1981 American Society of Civil Engineers Convention and Exposition, St. Louis, Mo. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

83. Kendall, M. G., and A. Stuart. 1976. The Advanced Theory of Statistics, Vol III, Hafner Press. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

84. Kittrell, F. W., and A. W. West. 1967. "Stream Survey Procedures," Journal of the Water Pollution Control Federation, Vol 39, pp 627-641. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

85. Knapp, R. T. 1942. "Density Currents: Their Mixing Characteristics and Their Effect on the Turbulence Structure of the Associated Flow," Proceedings, Second Hydraulic Conference, pp 289-306. Available from: University of Iowa, Iowa City, IA 52242.

86. Likens, G., and R. G. Wetzel. 1979. Limnological Methods, Academic Press. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

87. Loar, J. M., and M. J. Sale. 1981. "Analysis of Environmental Issues Related to Small-Scale Hydroelectric Development; V. Instream Flow Needs for Fishery Resources," Environmental Sciences Division Publication No. 1829 (ORNL/TM-7861). Available from: Oak Ridge National Laboratory, PO Box P, Oak Ridge, TN 37830.

88. Mood, A. M., and F. A. Graybill. 1974. Introduction to the Theory of Statistics, 3d ed., McGraw-Hill. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

89. Mortimer, C. H. 1974. "Lake Hydrodynamics," Mitt. Int. Ver. Theor. Agnew. Limnol., Vol 20, pp 124-197. Available from: National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

90. __________. 1981. "The Oxygen Content of Air-Saturated Fresh Waters Over Ranges of Temperature and Atmospheric Pressure of Limnological Interest," Mitt. Int. Ver. Theor. Agnew. Limnol., No. 22. Available from: National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

91. Murr, K. R. 1983. "Online Literature Searching," Journal of the Water Pollution Control Federation, Vol 55, pp 541-545. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

92. Norton, W. R., and I. P. King. 1977. "A Two-Dimensional Finite Element Program for Problems in Horizontal Free Surface Hydromechanics--Operating Instructions for the Computer Program RMA-2," Report to Association of Bay Area Governments. Available from: Resource Management Associates, Inc., Lafayette, CA 94549.

93. Organization for Economic Cooperation and Development. 1982. Eutrophication of Waters--Monitoring, Assessment, and Control, Synthesis Report of the OECD Cooperative Programme on Eutrophication, Paris. Available from: OECD Publications, 1750 Pennsylvania Ave., NW, Washington, DC 20006.

94. Reckow, K., and Chapra, S. C. 1983. "Engineering Approaches for Lake Management, Vol 1: Data Analysis and Empirical Modeling," Butterworth Publishers. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

95. Salas, J. D., J. W. Delleur, V. Yevjevich, and W. L. Lane. 1980. Applied Modeling of Hydrologic Time Series, Water Resources Publications, Littleton, Colo. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

96. SAS Institute, Inc. 1979. "SAS User's Guide." Available from: SAS Institute, Inc., SAS Circle, Cary, NC 27511.

97. Schofield, T. 1980. "Sampling of Water and Waste Water: Practical Aspects of Sample Collection," Water Pollution Control, Vol 79, No. 4, pp 468-476. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

98. Siegel, S. 1956. Nonparametric Statistics for the Behavioral Sciences, McGraw-Hill. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

99. Snedocor, G. W., and W. G. Cochran. 1979. Statistical Methods, 6th ed., Iowa State University Press. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

100. Sokal, R. R., and F. J. Rohlf. 1979. Biometry, W. H. Freeman and Co. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

101. Steel, H. M., and J. Torrie. 1980. Principles and Procedures of Statistics: A Biometric Approach. Available from: McGraw-Hill Book Co., 1221 Ave. of the Americas, New York, NY 10020.

102. Sutron Corporation. 1980. "Study of the Lateral and Longitudinal Mixing Characteristics of the Missouri River in Lewis and Clark Lake," Sutron Report No. SCR-348-80-035. Available from: US Army Engineer Division, Missouri River, PO Box 103 Downtown Station, Omaha, NE 68101.

103. Tennekes, H., and J. L. Lumley. 1972. A First Course in Turbulence. Available from: The MIT Press, 28 Carleton St., Cambridge, MA 02139.

104. Thornton, K. W., R. H. Kennedy, A. D. Magoun, and G. E. Saul. 1982. "Reservoir Water Quality Sampling Design," Water Resources Bulletin, Vol 18, pp 471-480. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

105. Tukey, John. 1977. Exploratory Data Analysis, Addison-Wesley. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

106. Vanoni, V. A. 1977. Sedimentation Engineering. Available from: American Society of Civil Engineers, 345 E 47th St., New York, NY 10017.

107. Walker, W. W. 1979. "Use of Hypolimnetic Oxygen Depletion Rates as a Trophic State Index for Lakes," Water Resouces Research, Vol 15, pp 1463-1470. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

108. Ward, J. V. 1976. "Effects of Flow Patterns Below Large Dams on Stream Benthos: A Review," Instream Flow Needs, Vol 2, pp 235-253, J. F. Orsborn and C. H. Allman, eds. Available from: American Fisheries Society, 15th St. and New York Ave., NW, Washington, DC 20005.

109. Ward, J. V., and J. A. Stanford, eds. 1979. The Ecology of Regulated Streams. Available from: Plenum Press, 233 Spring St., New York, NY 10013.

110. Wetzel, R. G. 1983. Limnology. Available from: Saunders College Publishing, W Washington Square, Philadelphia, PA 19105.

111. Winer, B. J. 1973. Statistical Principles in Experimental Design, 2d ed., McGraw-Hill. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

112. Yake, W. E., and R. K. James. 1983. "Setting Effluent Ammonia Limits to Meet In-Stream Toxicity Criteria," Journal of the Water Pollution Control Federation, Vol 55, pp 303-309. Available from: Technical Information Center, US Army Engineer Waterways Experiment Station, PO Box 631, Vicksburg, MS 39180-0631.

APPENDIX B
BIBLIOGRAPHY

a. Abidi, S. L. 1982. "Detection of Diethylnitrosamines in Nitrite-Rich Water Following Treatment with Rhodamine Flow Tracers," Water Research, Vol 16, No. 2, pp 199-204.

b. Allen, H. H. 1978. "Planting Techniques to Stabilize Reservoir Shoreline at Lake Wallula, Oregon/Washington," Environmental and Water Quality Operational Studies Information Exchange Bulletin E-78-2, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

c. Beyers, R. J. 1983. "The Metabolism of Twelve Aquatic Laboratory Microecosystems," Ecological Monographs, Vol 33, pp 281-306.

d. Bowman, G. T., and J. J. Delfino. 1980. "Sediment Oxygen Demand Techniques: A Review and Comparison of Laboratory and In Situ Systems," Water Resources, Vol 14, pp 491-499.

e. Chen, R. L., J. M. Brannon, and D. Gunnison. 1984. "Anaerobic and Aerobic Rate Coefficients for Use in CE-QUAL-RI," Miscellaneous Paper E-84-5, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

f. Churchill, M. A. 1958. "Effects of Storage Impoundments on Water Quality," Transactions of the American Society of Civil Engineers, Vol 123, pp 419-464.

g. Cochran, W. G. 1963. Sampling Techniques, John Wiley and Sons, Inc., New York.

h. Csanady, G. T. 1975. "Hydrodynamics of Large Lakes," Annual Review of Fluid Mechanics, Vol 7, pp 357-396.

i. Cummins, K. W. 1974. "Structure and Function of Stream Ecosystems," Bioscience, Vol 24, No. 1, pp 631-641.

j. Duthie, H. C., and M. L. Ostrofsky. 1975. "Environmental Impact of the Churchill Falls (Laboratory) Hydro-Electric Project: A Preliminary Assessment," Journal of the Fisheries Research Board of Canada, Vol 32, pp 117-125.

k. Ford, D. E., and K. W. Thornton. 1979. "Time and Length Scales for the One-Dimensional Assumption and Its Relation to Ecological Models," Water Resources Research, Vol 15, No. 1, pp 113-120.

l. Ford, D. E., K. W. Thornton, W. B. Ford III, and A. S. Lessem. 1979. "Water Quality Evaluation of Proposed Twin Valley Lake, Wild Rice River, Minnesota," Technical Report EL-79-5, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

m. Ford, D. E., K. W. Thornton, A. S. Lessem, and C. Stirgus. 1978. "Water Quality Evaluation of Proposed Trexler Lake, Jordan Creek, Pennsylvania," Technical Report Y-78-10, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

n. Gordon, J. A., and B. A. Skelton. 1977. "Reservoir Metalimnion Oxygen Demands," Journal of the Environmental Engineering Division, American Society of Civil Engineers, Vol 103, No. EE6, pp 1001-1011.

o. Graf, W. H. 1971. Hydraulics of Sediments Transport, McGraw-Hill, New York.

p. Gunnison, D. 1981. "Microbial Processes in Recently Impounded Reservoirs," American Society of Microbiology News, Vol 47, No. 12, pp 527-531.

q. Gunnison, D., and J. M. Brannon. 1981. "Characterization of Anaerobic Chemical Processes in Reservoirs: Problem Description and Conceptual Model Formulation," Technical Report E-81-6, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

r. Hannan, H. H. 1979. "Chemical Modifications in Reservoir Regulated Streams," The Ecology of Regulated Streams, J. V. Ward and J. A. Stanford, eds., Plenum Publishing, New York.

s. Hannan, H. H., D. Burrows, and D. C. Whitenberg. 1981. "The Trophic Status of a Deep-Storage Reservoir in Central Texas," Proceedings of the Symposium on Surface Water Impoundments, American Society of Civil Engineers, H. Stefan, ed., Vol I, pp 425-434.

t. Hannan, H. H., and T. M. Cole. 1984. "Dissolved Oxygen Dynamics in Reservoirs," Perspectives on Reservoir Ecosystems (in preparation), K. W. Thornton, ed., John Wiley and Sons, Inc., New York.

u. Higgins, J. M., and B. R. Kim. 1981. "Phosphorus Retention Models for Tennessee Valley Authority Reservoirs," Water Resources Research, Vol 17, pp 571-576.

v. Ivatin, A. V. 1974. "Production of Phytoplankton and Decomposition of Organic Matter in the Kuybyshen Reservoir," Hydrobiological Journal, Vol 10, pp 49-52.

w. Johnson, M. C. 1983. "Fluorometric Techniques for Tracing Reservoir Inflows," Instruction Report E-84-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

x. Kennedy, R. H., R. H. Montgomery, W. F. James, and J. Nix. 1983. "Phosphorus Dynamics in an Arkansas Reservoir: The Importance of Seasonal Loading and Internal Recycling," Miscellaneous Paper E-83-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

y. Kimmel, B. L., O. T. Lind, and L. J. Paulson. 1984. "Reservoir Primary Production," Perspectives on Reservoir Ecosystems (in preparation), K. W. Thornton, ed., John Wiley and Sons, Inc., New York.

z. Larson, D. W. 1979. Turbidity-Induced Meromixis in an Oregon Reservoir: Hypothesis," Water Resources Research, Vol 15, No. 6, pp 1560-1566.

aa. Linsley, R. K., and J. B. Franzini. 1972. Water Resources Engineering, 2d ed., McGraw-Hill, New York.

bb. Maciolek, J. A., and M. G. Tunzi. 1968. "Microseston Dynamics in a Simple Sierra Nevada Lake-Stream System," Ecology, Vol 49, No. 1, pp 60-75.

cc. Mathias, J. A., and J. Barica. 1980. "Factors Controlling Oxygen Depletion in Ice-Covered Lakes," Canadian Journal of Fisheries and Aquatic Sciences, Vol 37, pp 185-194.

dd. McKee, G. D. 1977. "Development and Operation of a Laboratory for Analyses of Water Quality Samples," Proceedings of a Seminar on Water Quality Data Collection and Management, 25-26 January 1977, Denver, Colo., US Army Corps of Engineers Committee on Water Quality.

ee. Morrisey, G. L. 1970. "Management by Objectives and Results in the Public Sector," Addison-Wesley, Boston, Mass.

ff. National Academy of Sciences. 1969. "Eutrophication: Courses, Consequences, and Correctives," Washington, DC.

gg. Nix, J. 1981. "Contribution of Hypolimnetic Water to Metalimnetic Dissolved Oxygen Minima in a Reservoir," Water Resources Research, Vol 17, pp 329-332.

hh. Novotny, J. F., and R. D. Hoyt. 1983. "Seasonal and Spatial Distribution of Zooplankton in a Flood Control Reservoir and Tailwater," Miscellaneous Paper E-83-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

ii. Olress, A., and D. Rausch. 1977. "Callahan Reservoir; III. Bottom Sediment-Water-Phosphorus Relationship," Transactions of the American Society of Agricultural Engineers, Vol 20, pp 291-297.

jj. Perrier, E. R., H. E. Westerdahl, and J. F. Nix. 1977. "Water Quality Loadings During Thirteen Storms in the Caddo River, Arkansas," American Society of Agricultural Engineers Meeting, Paper No. 77-2529, St. Joseph, Mo.

kk. Ploskey, G. R. 1981. "Factors Affecting Fish Production and Fishing Quality in New Reservoirs, With Guidance on Timber Clearing, Basin Preparation, and Filling," Technical Report E-81-11, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

ll. Prescott, G. W. 1968. The Algae: A Review, Houghton Mifflin, Boston, Mass.

mm. Shapiro, J. 1983. "Blue-Green Dominance in Lakes: The Role and Management Significance of pH and CO_2," EPA-440/5-83-001, US Environmental Protection Agency, Washington, DC.

nn. Soltero, R. A., J. C. Wright, and A. A. Horpestad. 1973. "Effects of Impoundment on the Water Quality of the Bighorn River," Water Research, Vol 7, No. 3, pp 343-354.

oo. Sorokin, Y. I. 1972. "Biological Productivity of the Rybinsk Reservoir," Proceedings of the IBP-UNESCO Symposium on Productivity Problems of Freshwaters, Z. Kajak and A. Hillbricht-Ilkowska, eds., Polish Scientific Publishers, Krakow.

pp. Thornton, K. W., D. E. Ford, and D. L. Robey. 1976. "Preliminary Evaluation of Water Quality of Proposed LaFarge Lake, Kickapoo River, Vernon County, Wisconsin," Miscellaneous Paper Y-76-5, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

qq. Thornton, K. W., D. E. Ford, D. L. Robey, R. L. Eley, and A. S. Lessem. 1977. "Preimpoundment Eutrophication Study Approaches," paper presented at American Society of Civil Engineers Fall Convention, San Francisco, Calif. (Preprint 3025).

rr. US Environmental Protection Agency. 1979. "Handbook for Analytical Quality Control in Water and Wastewater Laboratories," EPA-600/4-79-019, Environmental Monitoring and Support Laboratory, Cincinnatti, Ohio.

ss. Vallentyne, J. R. 1974. "The Algal Bowl--Lakes and Man," Miscellaneous Special Publication 22, Department of Environmental Fisheries and Marine Service, Ottawa, Canada.

tt. Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. "The River Continuum Concept," Canadian Journal of Fisheries and Aquatic Sciencies, Vol 37, pp 130-137.

uu. Westerdahl, H. E., W. B. Ford III, J. Harris, and C. R. Lee. 1981. "Evaluation of Techniques to Estimate Annual Water Quality Loadings to Reservoirs," Technical Report E-81-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

vv. Wilhelms, S. C., and D. R. Smith. 1981. "Reaeration Through Gated Conduit Outlet Works," Technical Report E-81-5, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

APPENDIX C
SAMPLE DESIGN CALCULATIONS:
DEVELOPMENT OF DECISION MATRIX (TABLE 5-1)

C-1. The decision matrix will be developed using examples for both the random and stratified random sampling formulas. Initially, use the random sampling formula

$$n = \frac{t^2 s^2}{d^2}$$

as previously defined to estimate the number of epilimnetic samples.

a. The variance s^2 is obtained from the variance component analysis performed on the pilot studies or from the routine sampling program. For this example, assume $s^2 = 100$.

b. Assume a desired precision level d to be, e.g., ±5 µg P/ℓ of a mean phosphorus concentration of 20 µg P/ℓ. Also assume a 90-percent probability of being within the desired precision level of the mean. Since the Student's t value for this probability level varies as a function of sample size, an $n = 30$ is used to initialize the sampling formula, so

$$n = \frac{(1.697)^2_{30,0.10}\ (100)}{(5)^2} = \frac{(2.88)(100)}{25} = 11.52$$

c. Round n to the next larger integer, 12; enter the t table at $\alpha = 0.10$ for $n = 12$ and repeat:

$$n = \frac{(1.782)^2_{12,0.10}\ (100)}{(5)^2} = \frac{(3.175)(100)}{25} = 12.7$$

d. Round to 13, reenter the t table and repeat:

$$n = \frac{(1.771)^2_{13,0.10}\ (100)}{(5)^2} = 12.5 \text{ (convergence at } n = 13)$$

e. To be within ±5 µg P/ℓ of the mean epilimnion P concentration 90 percent of the time, therefore, requires 13 randomly collected samples. Similar analyses performed at transect 10 or 12 for turbidity and chlorophyll, to be within a desired precision level 90 percent of the time, indicated 6 and 10 samples be randomly collected, respectively.

f. If one assumes a fixed cost of $500 per trip and a per sample analytical cost of $13 for phosphorus, $3 for turbidity, and $20 for chlorophyll, the cost per sampling trip is

$$C(n) = C_o + \sum_{1}^{k} C_i n_i$$

or

$$C(n) = 500 + (13)(13) + (3)(6) + (20)(10)$$

$$C(n) = 500 + 169 + 18 + 200$$

$$C(n) = \$887$$

If one samples 12 times per year, the total annual cost of sampling these three variables in the epilimnion is (12)(887) = $10,644 .

C-2. The decision matrix can now be expanded to include other alternatives. If, for example, a desired precision of ±10 μg P/ℓ about the mean P concentration 80 percent of the time is acceptable, the required number of phosphorus samples becomes

$$n = \frac{(1.310)^2_{30,0.20}\ (100)}{(10)^2} = \frac{(1.716)(100)}{100} = 1.7 \sim 2$$

$$\vdots$$

$$n = \frac{(1.638)^2_{3,0.20}\ (100)}{(10)^2} = 2.7$$

n = 3 random samples

a. Comparable reductions in the precision and probability levels for chlorophyll result in only three randomly collected epilimnetic samples.

b. If the turbidity precision and probability levels are maintained, the revised sampling costs per trip would be

$$C(n) = 500 + (13)(13) + (3)(6) + (20)(3)$$

$$= \$617/\text{sampling trip}$$

or $7,404 total annual cost (12 × $617) for epilimnetic sampling, a net savings of $3,240.

C-3. If we assume a variance s^2 for the metalimnion and hypolimnion of 144 and 169, respectively, a desired precision of ±5 µg P/ℓ about the mean P concentration with a 90-percent probability level, using the random sampling formula, results in 18 and 20 randomly collected samples from the metalimnion and hypolimnion, respectively. Therefore, to achieve these desired results, 51 random samples would have to be taken throughout the water column.

C-4. The stratified random sampling formula permits a weighting of the variance to reflect its relative importance in the system. While the variability may be greatest in the hypolimnion, the hypolimnion may represent only 30 percent of the entire volume.

a. If we assume the cost of sampling each stratum is constant, the stratified random sampling formula is

$$n = \frac{(\Sigma w_i s_i)^2}{d^2/t^2}$$

as previously defined. If we assume the same desired precision and probability levels, i.e. ±5 µg P/ℓ, 90-percent probability, and weight by stratum volume, then

$$w_{\text{epilimnion}} = 0.40$$

$$w_{\text{metalimnion}} = 0.20$$

$$w_{\text{hypolimnion}} = 0.40$$

$$n = \frac{[(0.4)(10) + (0.2)(12) + (0.4)(13)]^2}{(5)^2/(1.697)^2_{30,0.10}}$$

$$= 15.5$$

$$n = \frac{[(0.4)(10) + (0.2)(12) + (0.4)(13)]^2}{(5)^2/(1.746)^2_{16,0.10}}$$

$$n = 16.4$$

$$n = \frac{[(0.4)(10) + (0.2)(12) + (0.4)(13)]^2}{(5)^2/(1.74)^2}$$

$$n = 16.3$$

$$n = 17$$

The total number of samples using a stratified approach, therefore, has been reduced from 51 to 17.

b. The required number of randomly collected samples per stratum is

$$\frac{n_i}{n} = \frac{w_i s_i}{\Sigma(w_i s_i)}$$

$$\frac{n_e}{17} = \frac{(0.4)(10)}{[(0.4)(10) + (0.2)(12) + (0.4)(13)]}$$

$$= 5.9$$

$$\sim 6$$

$$\frac{n_m}{17} = \frac{(0.2)(12)}{[(0.4)(10) + (0.2)(12) + (0.4)(13)]}$$

$$= 3.5$$

$$\sim 4$$

$$\frac{n_h}{17} = \frac{(0.4)(13)}{[(0.4)(10) + (0.2)(12) + (0.4)(13)]}$$

$$= 7.6$$

$$\sim 8$$

$$n = 18$$

c. Similar computations can be made for each of the other water quality variables.

C-5. The cost of the sampling program again can be computed using the cost formula. As previously described, a decision matrix can be developed that reflects various probability and precision levels to satisfy funding constraints.

C-6. The sampling formula can also be used to assess the loss of precision if fixed numbers of samples are collected at each station. It is, perhaps, not realistic to expect a field crew to collect variable numbers of samples for water quality constituents at each station. If it is determined that six samples will be collected from the epilimnion, four samples from the metalimnion, and eight samples from the hypolimnion, the precision for each constituent can be determined by rearranging the sampling formula as

$$d = \frac{ts}{\sqrt{n}} \text{ for the random sampling formula}$$

and

$$d = \frac{(\Sigma w_i s_i)t}{\sqrt{n}} \text{ for the stratified random sampling formula}$$

a. For chlorophyll, which will be collected in the epilimnion, six samples will result in a precision, at the 90-percent probability level, of

$$d = \frac{(1.943)(3.5)}{\sqrt{6}} = 2.78$$

$$= \pm 40 \text{ percent}$$

b. Six samples have reduced the precision from ±25 percent for chlorophyll to ±40 percent, but this loss, or gain, in precision is now known and can be calculated.

C-7. In general, use of the stratified random sampling formula results in a more cost-effective, efficient sampling design than using the random sampling approach.

APPENDIX D
ORDER OF MAGNITUDE ESTIMATES

D-1. Purpose. The purpose of an order of magnitude estimate is to provide quick and general insight into water quality characteristics, phenomena, or processes occurring within the reservoir. Table 2-2 summarizes the algorithms used in order of magnitude analyses. These should be used only as "first cut" or preliminary computations to more detailed analyses.

D-2. Morphometric and Hydrologic Characteristics.

a. Collated Characteristics. Collated characteristics are the intrinsic physical properties of the reservoir that are used in order of magnitude computations. These parameters are usually reported in Design Memoranda and include shoreline length (L_s), surface area (A), volume (V), reservoir length (L), maximum depth (Z_m), outlet elevation (Z), normal pool elevation (Z_n), spillway elevation (Z_s), and watershed drainage area (DA). These properties must be known before any calculated characteristics are determined.

b. Calculated Characteristics. One or more of the collated characteristics is often used in an expression to define other water quality characteristics. These include:

(1) Mean depth, the volume (V) divided by the surface area (A) (both at normal pool unless specified otherwise). In general, mean depth is inversely related to productivity. Reservoirs with large mean depths generally are less productive than reservoirs with small mean depths.

$$Z = V/A$$

(2) Development of volume, mean depth (Z) divided by maximum depth (Z_m). A value of 0.33 represents a perfect conical depression.

$$Z/Z_m$$

(3) Mean breadth, the average width of the reservoir determined by dividing the surface area (A) by the maximum length of the reservoir (L) (see Ref. 110, Appendix A). Large mean breadth ratios indicate the potential for large fetches and waves.

$$\bar{b} = A/L$$

(4) Drainage area to surface area ratio, which is usually large for reservoirs with the potential for high sediment and nutrient loads, shorter residence times, and greater areal water loads.

$$DA/SA$$

(5) Shoreline development ratio, the ratio of the shoreline length (L_s) to the circumference of a circle of area equal to the surface area (A) of the reservoir (Ref. 110). Large ratios indicate very irregular or dendritic systems. Dendritic systems usually have numerous coves and embayments, or extensive littoral areas and, therefore, the potential for greater biological activity.

$$D_L = L_s/(2\sqrt{\pi A})$$

(6) Mean hypolimnion depth, product of mean depth (Z) and percentage of the total depth below the thermocline (Ref. 107). This can provide an estimate of the volume of oxygen available to satisfy oxygen demand. Shallow hypolimnetic depths can indicate the potential for anoxia.

$$Z_H = Z(1 - Z_T/Z_m)$$

(7) Relative depth, ratio of the maximum depth (Z_m) as a percentage of a "diameter" of the reservoir (derived from its surface area, A) (Ref. 110). In general, the smaller the relative depth, the greater the influence of wind in disrupting thermal stratification.

$$Z_r = 50\ Z_m\sqrt{\pi/A}$$

(8) Hydraulic residence time, ratio of reservoir volume (V) to outflow rate. A short residence time is indicative of a high flushing rate in the pool.

$$\tau = V/Q$$

(9) Flushing rate, inverse of the hydraulic residence time (τ). If $\alpha < 10$, the reservoir may stratify; if $\alpha < 20$, the reservoir may be well mixed. Values around 10 can indicate a weakly stratified system (Ref. 32).

$$\alpha = 1/\tau$$

(10) Single storm flushing rate, the average inflow rate for a given storm event (Q_s) divided by the reservoir volume (V) (Ref. 32). If $\beta < 0.5$, the storm inflow may not mix the reservoir. If $\beta < 1$, the storm inflow may mix the reservoir.

$$\beta = Q_s/V$$

(11) Densimetric Froude number, the ratio of inertial to buoyancy forces in a stratified system. The system is classified as strongly stratified if $F_d \ll 1/\pi$. When $F_d \gg 1/\pi$ the system is well mixed. The system is weakly

or intermittently stratified when F_d is approximately equal to $1/\pi$ (Ref. 32).

$$F_d = 320 * \frac{LQ}{ZV}$$

(12) Plunge point depth, the point at which denser inflowing river water plunges beneath the surface water of the pool and becomes a density current (Ref. 67). The critical densimetric Froude number, F_p, typically varies between 0.1 and 0.7. The normalized density difference, $\Delta\rho/\rho$, is the density difference between the inflow and the surface water divided by the density of the surface water.

$$D = \left(\frac{1}{F_\rho}\right)^{1/3} \left[Q^2 / \left(W^2 \cdot g \cdot \frac{\Delta\rho}{\rho}\right)\right]^{1/3}$$

D-3. Physical Relationships. Various physical relationships can be approximated by simple algorithms and are presented herein. Table 2-2 summarizes these relationships.

a. Water Density. This can be expressed in terms of contributions from temperature, total dissolved solids (TDS), and suspended solids (SS).

$$\rho_W = \rho_T + \Delta\rho_{TDS} + \Delta\rho_{SS}$$

$$\rho_T = 1{,}000 - \frac{(T - 3.98)^2\ (T + 283)}{(503.57)(T + 67.26)}$$

$$\Delta\rho_{TDS} \sim 0.00078 * C_{TDS}$$

$$\Delta\rho_{SS} \sim 0.00062 * C_{SS}$$

b. Viscosity. This describes the inertial "friction" of a fluid. A fluid with a high viscosity offers high resistance to shear stress. The viscosity of a fluid can be estimated given the temperature and density of the fluid. Since viscosity decreases with increasing temperature, particulate matter (i.e., algae, SS) will settle faster at higher temperatures.

$$\nu = \rho(0.069\ T^2 - 5.3T + 177.6)$$

c. Settling Velocity. This defines the velocity of a particle of diameter D and density ρs settling in a fluid of density ρ and viscosity (Ref. 106).

$$v_s = \frac{gD^2}{18\nu} (\rho s - \rho)$$

d. Sedimentation Index. This is the ratio of the hydraulic residence time τ to the theoretical mean velocity through the reservoir $Q/(V/L)$ (Ref. 75). The sedimentation index indicates the sediment retention in the reservoir (i.e., trap efficiency).

$$S_I = \tau/(QL/V)$$

e. Areal Erosion. This is the percentage of lake bed area subject to the processes of erosion and transportation (Ref. 72). It may be estimated knowing only the surface area and mean depth of the reservoir.

$$a_{E+T} = 1{,}090 \sqrt{A}/Z * \exp (Z/\sqrt{A})$$

D-4. Chemical Relationships. Several chemical relationships also can be approximated by simple algorithms. These relationships are also summarized in Table 2-2.

a. Dissolved Oxygen Saturation Concentration. This can be approximated given the water temperature (T,°C), and elevation sea level (h, km) (Ref. 90). Since oxygen concentration regulates many aquatic processes, including the life of many organisms, the relation of the actual DO concentration to potential saturated concentrations can indicate if significant oxygen demand is occurring.

$$\begin{aligned} DO_{sat} = \exp (&7.7117 - 1.31403 * \ln (T + 45.93) \\ &+ 5.25 * \ln (1-h/44.3)) \end{aligned}$$

b. Oxygen Supply. This is the effective number of days of oxygen supply present in the hypolimnion at the onset of stratification (Ref. 107). It is defined as the ratio of the product of the oxygen supply at the onset of stratification (DO_i, g/m^3) and mean hypolimnion depth (Z_H, m) to the rate of change of the hypolimnetic oxygen deficit (ΔHOD, $g/m^2 \cdot$ day). If the stratified period is longer than the days of oxygen supply, anoxic conditions can occur.

$$T_{DO} = DO_i * Z_H/\Delta HOD$$

c. Un-ionized Ammonia. The potentially toxic fraction of total ammonia in solution can be estimated given effluent and upstream flow rates (Q_e and Q_u, respectively) and total ammonia concentrations ($NH_4 + NH_3^o$ expressed as nitrogen) (C_e^T and C_u^T, respectively) and downstream temperature and pH (T_d and pH_d, respectively) (Ref. 112). This value can be compared with the water quality criterion or standard for un-ionized ammonia.

$$NH_3^{UI} = [(1 + 1/\ln (0.09019 + 2,729.92/T_d - pH_d)]$$

$$* (C_e^T Q_e + C_u^T Q_u)/(Q_e + Q_u)$$

d. Nitrogen Supersaturation Potential. Several methods for determining the potential for gas supersaturation at dams with deep stilling basins are discussed in detail in ETL 1110-2-239.

e. Total Dissolved Solids. This may be roughly estimated from specific conductance concentrations. TDS concentrations can influence inflow patterns.

$$TDS - 0.6 * \text{Specific Conductance}$$

f. Soluble Reactive Phosphorus (SRP). This may be estimated as approximately 40 to 50 percent of total phosphorus concentrations (TP) (Ref. 34). SRP is generally considered as biologically available and may indicate the potential for algal blooms.

$$SRP \sim (0.4 \text{ to } 0.5) * TP$$

GLOSSARY

TERMS

Absorption: Penetration of a substance into the body of another.

Accuracy: The ratio of the difference between the approximate solution obtained using a numerical model and the exact solution of the governing equations, divided by the exact solution.

Adjustment: Variation of the parameters in a model to ensure a close reproduction by the model of a set of prototype conditions.

Adsorption: The concentration of gases, dissolved materials, or ions on the surface of solid particles.

Aeration: A process in which water is treated with air or other gases, usually oxygen. In lake restoration, aeration is used to prevent anaerobic conditions or to provide artificial destratification.

Aerobic: Living or active only in the presence of oxygen.

Algal bloom: A high concentration of a specific algal species in a water body, usually caused by nutrient enrichment.

Algorithm: A set of numerical steps or routines to obtain a numerical output from a numerical input.

Alkalinity: A quantitative measure of water's capacity to neutralize acids. Alkalinity results from the presence of bicarbonates, carbonates, hydroxides, salts, and occasionally borates, silicates, and phosphates. Numerically, it is expressed as the concentration of calcium carbonate that has an equivalent capacity to neutralize strong acids.

Allochthonous: Describes organic matter produced outside of a specific stream or lake system.

Alluvial: Pertaining to sediments gradually deposited by moving water.

Anaerobic: Living, active, or occurring in the absence of free oxygen.

Analytical model: Mathematical model in which the solution of the governing equations is obtained by mathematical analysis, as opposed to numerical manipulation.

Anoxic: Devoid of free oxygen.

Aquifer: (1) A wholly saturated water-bearing stratum or zone of permeable rock below the surface of the earth capable of producing water from a well;

(2) Stratum or zone below the surface of the earth capable of producing water as from a well.

Autochthonous: Any organic matter indigenous to a specific stream or lake.

Autotrophic: The ability to synthesize organic matter from inorganic substances.

Basin: (1) Drainage area of lake or stream, such as a river basin; (2) Naturally or artifically enclosed harbor for a small craft, such as a turning basin for tows, or a yacht basin.

Benthic oxygen demand: Oxygen demand exerted from the bottom of a stream or lake, usually by biochemical oxidation of organic material in the sediments.

Benthos: Organisms living on or in the bottom of a body of water.

Bioassay: The use of living organisms to determine the biological effect of some substance, factor, or condition.

Biochemical oxidation: The process by which bacteria and other microorganisms break down organic material and remove organic matter from solution.

Biochemical oxygen demand (BOD): The amount of oxygen used by aerobic organisms to decompose organic material. Provides an indirect measure of the concentration of biologically degradable material present in water or wastewater.

Biomass: The total mass of living organisms in a particular volume or area.

Biome: A major kind of community, conceived in terms of form and structure of its plant and animal constituents.

Biota: All living matter in a particular region.

Blue-green algae: The phylum Cyanophyta, characterized by the presence of blue pigment in addition to green chlorophyll, which generally creates water quality concerns.

Boundary conditions (numerical models): Definition or statement of conditions or phenomena occurring at the boundaries of the model.

Boundary conditions (physical models): Conditions entered at the spatial boundaries of the model.

Calibration: Process of checking, adjusting, or standardizing operating characteristics of instruments and model appurtenances on a physical model or coefficients in a mathematical model. The process of evaluating the scale readings of an instrument in terms of the physical quantity to be measured.

Catchment: Surface drainage area.

Chemocline: A stratum of stronger concentration gradient of dissolved substances.

Chlorophyll: Green pigment in plants and algae necessary for photosynthesis.

Circulation period: The interval of time in which the thermal stratification of a lake is destroyed, resulting in the mixing of the entire water body.

Clinograde: The stratification curve of temperature or of a chemical substance in water that exhibits a uniform slope from the surface into deep water.

Conceptual model: Simplification of prototype behavior used to demonstrate concepts.

Convergence: State of tending to a unique solution. A given scheme is convergent if an increasingly finer computational grid leads to a more accurate approximation of the unique solution. Note that a numerical method may sometimes converge on a wrong solution.

Dam: Barrier constructed across a valley for impounding water or creating a reservoir, usually with facilities to control the release of impounded waters.

Densimetric Froude number: The ratio of inertial to buoyancy forces in a stratified system.

Denitrification: Reduction from nitrate to nitrite and further to elemental nitrogen.

Densimetric Froude number model: Model of gravity-dominated flow usually being densimetric Froude number scaling. Buoyant jets and stratified flows are examples.

Deterministic model: Mathematical model in which the behavior of every variable is completely determined by the governing equations.

Detritus: Finely divided organic or inorganic settleable material suspended in the water.

Dimensional analysis: Derivation of dimensionless ratios, based on the fact that functional relationships (for both model and prototype) must be dimensionally homogeneous.

Dimensionless number: Physically meaningful ratio of parameters that is dimensionless. These dimensionless ratios are useful in determining scaling laws since a particular dimensionless number must be the same in model and prototype to achieve similarity. Examples are the common force ratios, such as Froude and Reynolds numbers.

Dissolved solids: The difference between the total and suspended solids in water.

Distorted model: Hydraulic model in which horizontal and vertical scales are different.

Diversion: A channel or berm constructed across or at the bottom of a slope for the purpose of intercepting surface runoff.

Drainage basin, watershed, drainage area: A geographical area where surface runoff from streams and other natural watercourses is carried by a single drainage system to a common outlet.

Dynamic model: A mathematical model in which time is included as an independent variable.

Empirical model: Representation of a real system by a mathematical description based on experimental data rather than on general physical laws.

Enrichment: The addition to or accumulation of plant nutrients in water.

Epilimnion: The upper, circulating layer of a thermally stratified lake.

Erosion: The process by which the soil particles in situ are detached and transported by water or wind action and gravity to some downslope or downstream deposition point.

Eutrophic: Waters with a good supply of nutrients and hence a rich organic production.

Eutrophication: A natural enrichment process of a lake, which may be accelerated by man's activities. Usually manifested by one or more of the following characteristics: (1) excessive biomass accumulations or primary producers, (2) rapid organic and/or inorganic sedimentation and shallowing, or (3) seasonal and/or diurnal dissolved oxygen deficiencies.

Flood capacity: The flow carried by a stream or floodway at bankfull water level. Also, the storage capacity of the flood pool at a reservoir.

Froude number: Dimensionless number relating the velocity of flow to the speed of propagation of a small disturbance; the ratio of inertial forces to gravitational forces.

Gaging station: A selected section of a stream channel equipped with a gage, recorder, and/or other facilities for determining stream discharge.

Green algae: Algae characterized by the presence of photosynthetic pigments similar in color to those of the higher green plant.

Headwaters: (1) Upper reaches of stream near its source; (2) Region where ground waters emerge to form a surface stream; (3) Water upstream from a structure.

Heavy metals: Metals of high specific gravity, including cadmium, chromium, cobalt, copper, lead, mercury. These are toxic to many organisms, even in low concentrations.

Herbicide: Any chemical substance or mixture of substances intended to prevent, destroy, repel, or mitigate the growth of any tree, bush, weed, algae, and other aquatic needs.

Heterograde: A curve for temperature or a chemical factor in a body of water that exhibits a nonuniform slope from the surface downward into deep water.

Heterotrophic: The nutrition of plants and animals that are dependent on organic matter for food.

Heuristic model: Representation of a real system by a mathematical description based on reasoned, but unproven argument.

Holomictic: Lakes that are completely circulated to the bottom at the time of winter cooling.

Hydraulic model: Physical model using water as fluid.

Hydroelectric: Producing or relating to the production of electricity by water power.

Hydrograph: A continuous graph showing the properties of streamflow with respect to time.

Hydrologic cycle: The movement of water from the oceans to the atmosphere and back to the sea. Many subcycles exist, including precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transpiration.

Hydrology: Science dealing with the occurrence, circulation, distribution, and properties of the waters of the earth and its atmosphere.

Hypolimnion: The deep layer of a lake lying below the metaliminion and removed from surface influences.

Infiltration: Water entering the ground-water system throughout the land surface.

Initial conditions: Given values of dependent variables or relationship between dependent and independent variables at the time of startup of the computation.

Interactive model: Numerical model that allows interaction by the modeler during computation.

Laboratory effect: Consequence of necessary laboratory simplifications or physical constraints on the model.

Limiting nutrient: The substance that is limiting to biological growth due to its short supply with respect to other substances necessary for the growth of an organism.

Limnology: The study of inland waters.

Linear model: Mathematical model based entirely on linear equations.

Littoral: The shoreward region of a body of water.

Lock: Enclosed part of a waterway equipped with gates that allow water levels to change in order to raise or lower boats.

Macrophytes: Large vascular aquatic plants that are either rooted or floating.

Mathematical model: Model using mathematical relationships to represent the prototype.

Meromictic lakes: Those lakes that at the time of winter cooling undergo only a partial circulation down to a depth determined by a density stratification.

Mesotrophic lake: A trophic condition between an oligotrophic and an eutrophic water body.

Metalimnion: The layer of water in a lake between the epilimnion and hypolimnion in which the temperature exhibits the greatest difference in a vertical direction.

Monimolimnion: The deep water of a meromictic lake that is not involved in the annual circulation.

Monte Carlo method: Technique of stochastic sampling or selection of random numbers to generate synthetic data.

Net production: The assimilation surplus in a given period of time after subtracting the amount of dissimilation in the same time interval.

Neutralization: The process of adding an acidic or alkaline material to wastewater and/or surface water runoff to adjust its pH to a neutral condition.

Nitrification: The biochemical oxidation process by which ammonia is changed first to nitrites and then to nitrates by bacterial action.

Nitrogen, available: Includes ammonium, nitrate ions, ammonia, and certain simple amines readily available for plant growth.

Nitrogen cycle: The sequence of biochemical changes in which atmospheric nitrogen is "fixed," then used by a living organism, liberated upon the death and decomposition of the organism, and reduced to its original state.

Nitrogen, fixation: The biological process of removing elemental nitrogen from the atmosphere and incorporating it into organic compounds.

Nitrogen, organic: Nitrogen components of biological origin such as amino acids, proteins, and peptides.

Nonlinear model: Mathematical model using one or more nonlinear equations.

Nonpoint source: Pollutants that are not traceable to a discrete origin, but generally result from land runoff, precipitation, drainage, or seepage.

Numerical model: Mathematical model in which the governing equations are not solved analytically. Using discrete numerical values to represent the variable involved and using arithmetic operations. The governing equations are solved approximately.

Nutrient, available: That portion of an element or compound that can be readily absorbed and assimilated by growing plants.

Oligotrophic lake: A lake with a small supply of nutrients, and consequently a low level of primary production.

One-dimensional model: Model defined on one space coordinate, i.e., variables are averaged over the other two directions, e.g., pipe flow models and numerical models of long wave propagation in a narrow channel.

Orthograde: A stratification curve for temperature or a chemical factor in a body of water that has a straight uniform course.

Orthophosphate: See phosphorus, available.

Outfall: The point where wastewater or drainage discharges from a sewer to a receiving body of water.

Overturn: The complete mixing of a previously thermally stratified lake. This occurs in the spring and fall when water temperatures in the lake are uniform.

Oxidation: The removal of electrons from an ion or atom.

Oxygen deficit: The difference between observed oxygen concentrations and the amount that would be present at 100-percent saturation at a specific temperature.

Peak discharge: The maximum instantaneous flow from a given storm condition at a specific location.

Penstock: Conduit for controlling flow of water through a structure.

Periphyton: Microorganisms that are attached to or growing on submerged surfaces in water.

Pesticides: Any herbicide, insecticide, or rodenticide, excluding those nontoxic repellents or other chemicals.

Phosphorus, available: Phosphorus that is readily available for plant growth. Usually in the form of soluble orthophosphates.

Phosphorus, total (TP): All of the phosphorus present in a sample regardless of form. Usually measured by the persulfate digestion procedure.

Physical model: Model using the physical properties and behavior of modeling materials to represent the prototype.

Photosynthesis: The process occurring in green plants in which light energy is used to convert inorganic compounds to carbohydrates. In this process, carbon dioxide is consumed and oxygen is released.

Phytoplankton: Plant microorganisms, such as algae, living unattached in the water.

Plankton: Unattached aquatic microorganisms that drift passively through water.

Point source: Any discernible, confined, and discrete pipe, channel, ditch, tunnel, conduit, well, discrete fissure, or container that discharges or releases pollutants into water.

Population equivalent: An expression of the amount of a given waste load in terms of the size of human population that would contribute the same amount of biochemical oxygen demand per day.

Primary production: The production of organic matter from light energy and inorganic materials, by autotrophic organisms.

Probabilistic model: Mathematical model in which the behavior or one or more of the variables is either completely or partially described by equations of probability.

Project flood: A hypothetical flood selected as the guide for determining the size of engineering features of a project, such as levee height, floodway width, channel and storage size.

Prototype: The full-sized structure, system process, or phenomenon being modeled.

Reduction: The gaining of electrons.

Regulating: Reducing fluctuations of the outflow of water from an upstream project to smooth the flow and make it more uniform and even.

Reservoir: Pond, lake, basin, or other space, either natural or created in whole or in part by building of a structure such as a dam, that is used for storage, regulation, and control of water for power navigation, recreation, etc.

Reynolds number: Dimensionless ratio of inertial forces to viscous forces.

River basin: A portion of a water resource region, defined by a hydrological boundary.

Runoff: That part of precipitation that flows over the land surface from the area upon which it falls.

Scale: Ratio of a variable in a model to the corresponding variable in the prototype.

Scouring: The clearing and digging action of flowing water, especially the downward erosion caused by stream water in sweeping away mud and silt, usually during a flood.

Secchi depth: A measure of optical water clarity as determined by lowering a weighted Secchi disk into a water body to the point where it is no longer visible.

Sediment basin: A structure designed to slow the velocity of runoff water and facilitate the settling and retention of sediment and debris.

Seiche: A standing wave in a lake.

Similarity: Correspondence between the behavior of a model and its prototype.

Simulation: Replication of the prototype using a model.

Simulation model: Mathematical model that is used with actual or synthetic input data, or both, to produce long-term time series or predictions.

Specific gravity: A ratio that denotes how many times heavier a body is than the same volume of water at 4° C.

Specific heat: The quantity of heat in calories that must be added to a unit weight of a substance in order to raise its temperature 1° C.

Stability (numerical or computational): Ability of a scheme to control the propagation or growth of small perturbations introduced in the calculations.

Stage: Elevation of water surface above or below an arbitrary figure.

Standing crop: The biomass present in a body of water at a particular time.

Steady-state model: Model in which the variables being investigated are independent of time.

Stochastic model: See probabilistic model.

Subbasin: A physical division of a larger basin, associated with one reach of the storm drainage system.

Substrate: The substance or base upon which an organism grows.

Suspended solids: refers to the particulate matter in a sample, including the material that remains dispersed.

Thermal stratification: The layering of water bodies due to temperature-induced density differences.

Thermocline: The plane with the maximum rate of change in temperation or inflection in the temperature curve through the metalimnion.

Three-dimensional model: Model defined on three space coordinates, e.g., coastal models and numerical models of explosions.

Total solids: The solids in water, sewage, or other liquids, including the dissolved, filterable, and nonfilterable solids. The residue left when a sample is evaporated and dried at a specified temperature.

Trace elements: Those elements that are needed in low concentrations for the growth of an organism.

Tributary: Stream or other body of water that contributes its water to another stream or body of water.

Trophic condition: A relative description of a lake's biological productivity. The range of trophic conditions is characterized by the terms oligotrophic for the least biologically productive, to eutrophic for the most biologically productive.

Turbidity: A measure of the cloudiness of a liquid. Turbidity provides an indirect measure of the suspended solids concentration in water.

Turbulence: Unorganized movement in liquids and gases resulting from eddy formation.

Two-dimensional model: Model defined on two space coordinates, i.e., variables are averaged over the third direction (e.g., wave flume experiments, numerical models of storm surges).

Unsteady-state model: Model in which the variables being investigated are time dependent.

Validation: Comparison of model results with a set of prototype data not used for verification. Comparison includes: (1) using a data set very similar to the verification data to determine the validity of the model under conditions for which it was designed; (2) using a data set quite different from the verification data to determine the validity of the model under conditions for which it was not designed but could possibly be used; (3) using postconstruction prototype data to determine the validity of the predictions based on model results.

Verification: Check of the behavior of an adjustment model against a set of prototype conditions.

Viscosity: Resistance to flow in a liquid.

Water quality: A term used to describe the chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose.

Water quality standards: State-enforced standards describing the required physical and chemical properties of water according to its designated uses.

Watershed: See drainage basin.

Zooplankton: Protozoa and other animal microorganisms living unattached in water.