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

	Characteristics				
Method	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).

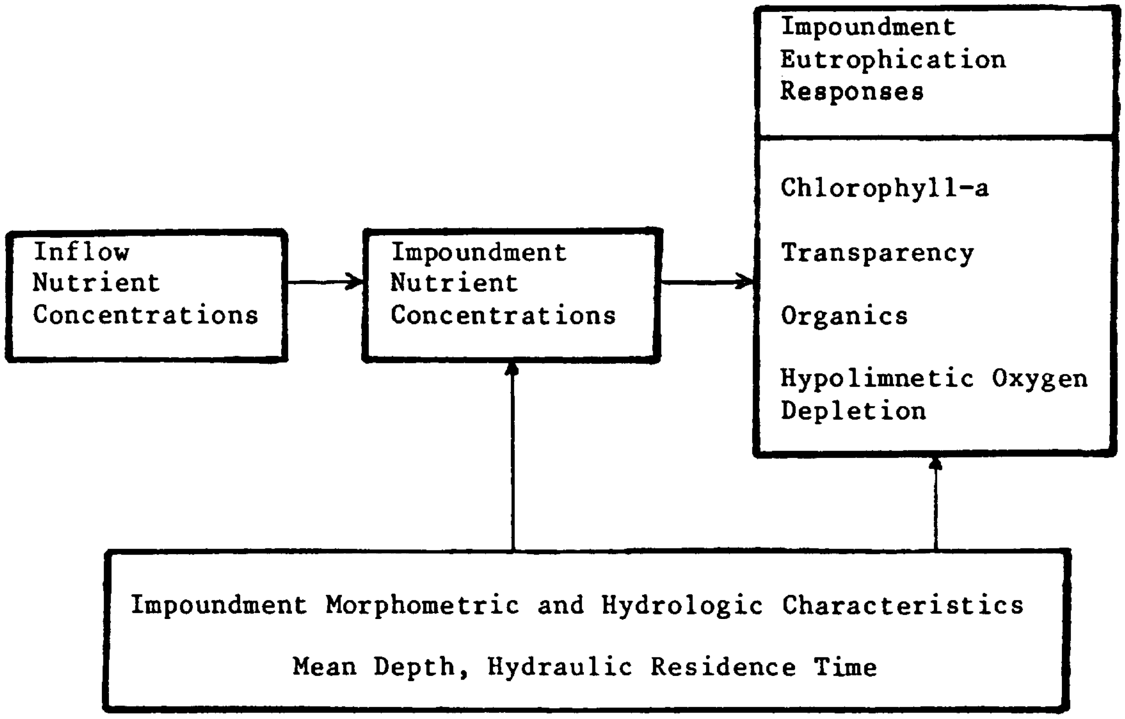


Figure 4-2. Control pathways in a typical nutrient loading model

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

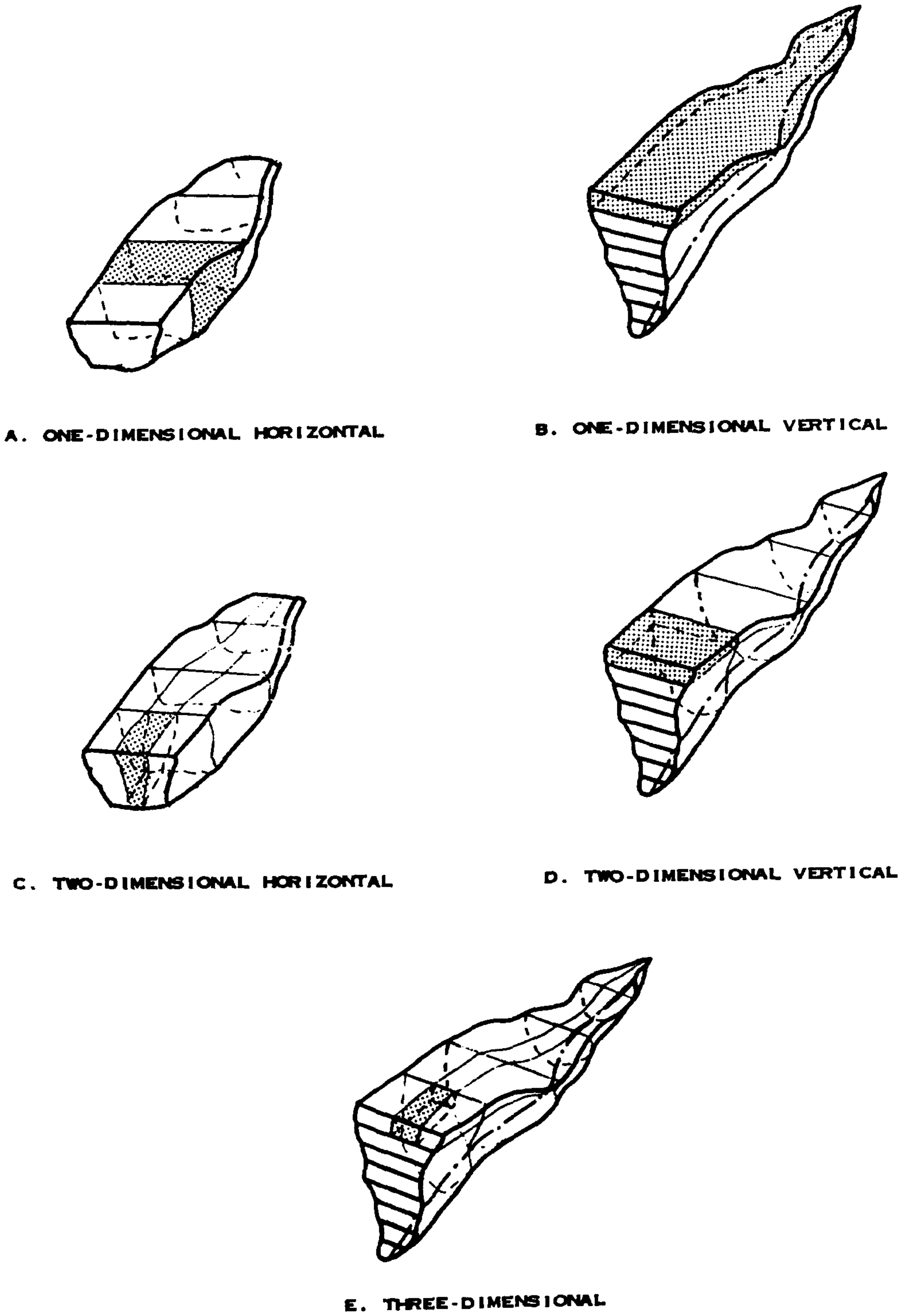


Figure 4-3. Comparison of model dimensions

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.

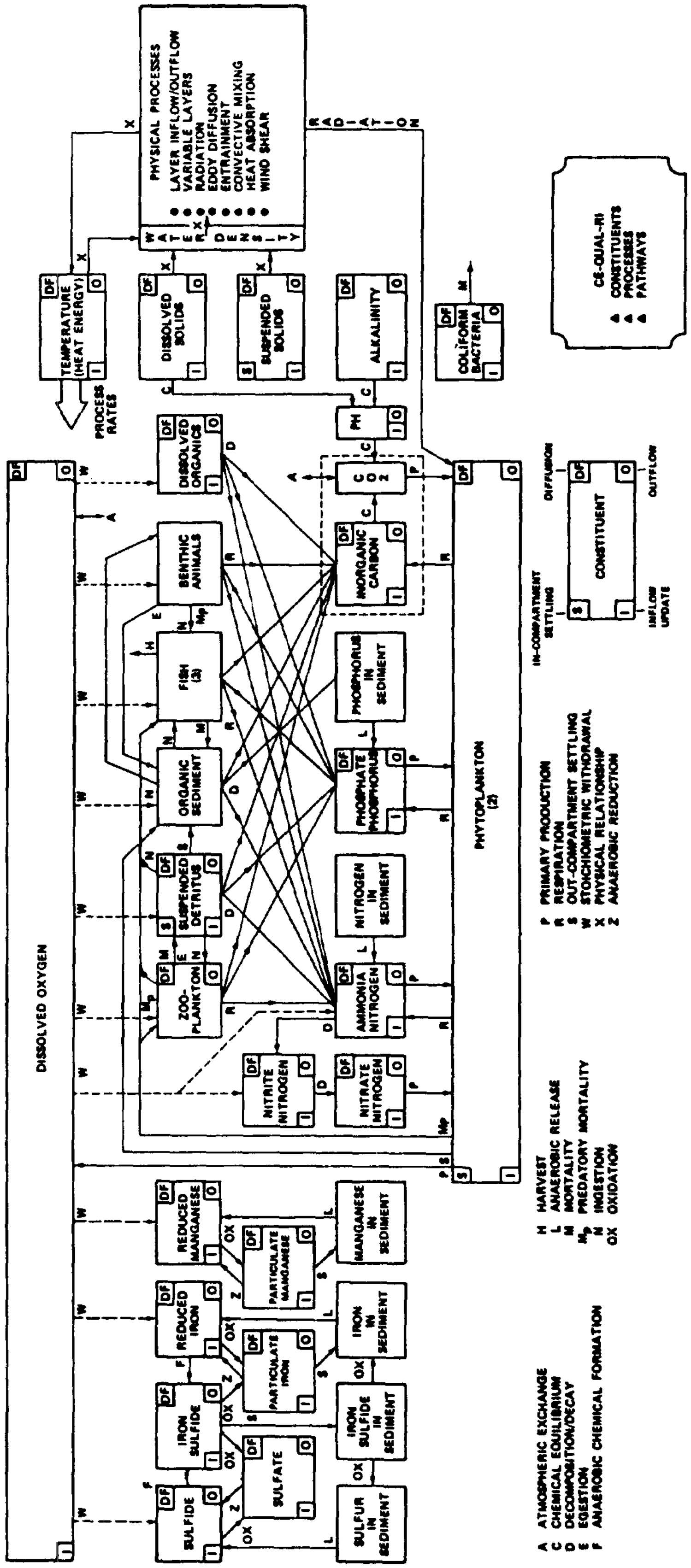


Figure 4-4. Typical water quality model constituents and pathways (from CE-QUAL-R1, Ref. 10)

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

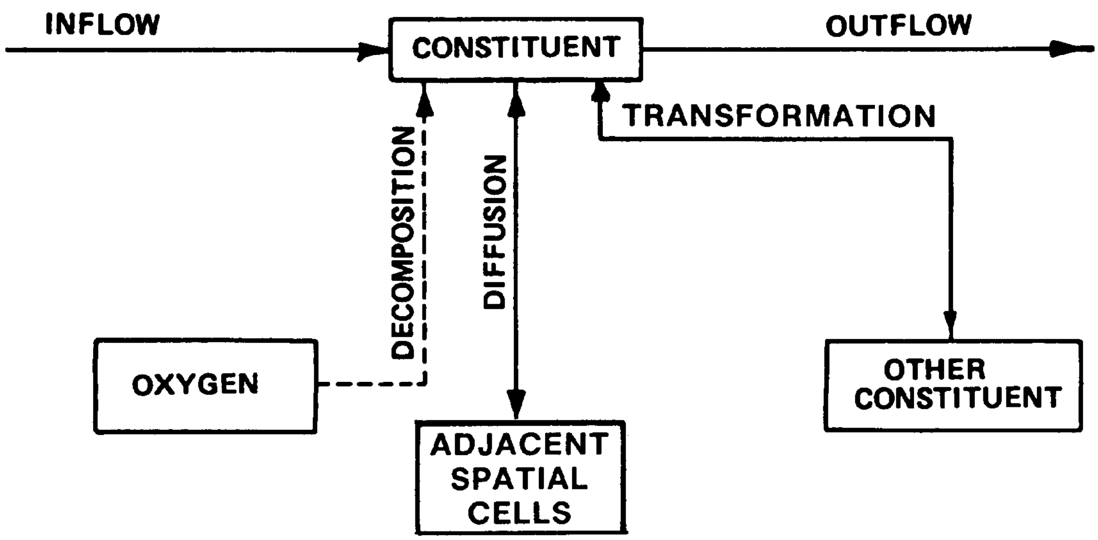


Figure 4-5. Model representation for conservation of mass

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

(2) One-dimensional vertical.

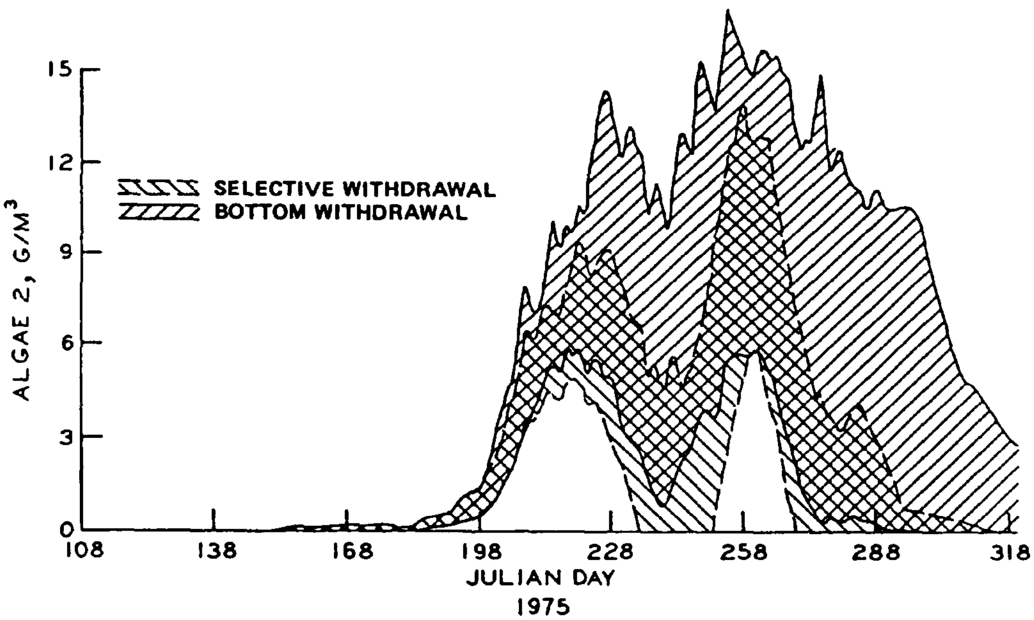
(a) Description. One-dimensional vertical reservoir or lake models consider the water body to be represented by a vertical series of well-mixed horizontal layers (Figure 4-3b). The models usually simulate the time-varying vertical distribution of constituents. The number and type of constituents considered 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.

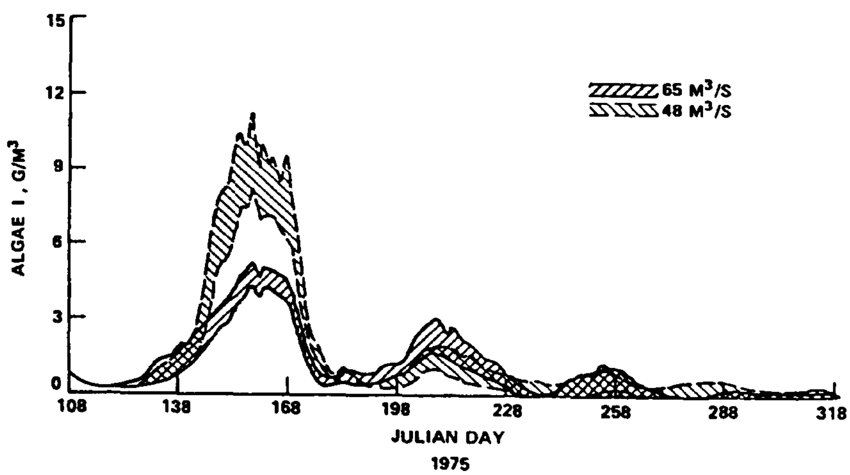
(c) Specific problems addressed. One-dimensional vertical models such as CE-QUAL-R1 (Ref. 10) can be used to address the following: seasonal variations in thermal stratification and DO, including the development of anoxic conditions; effect of structural modifications (i.e., selective withdrawal) and 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.