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Simplified Procedures for Eutrophication Assessment and Prediction: User Manual

by William W. Walker

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Prepared for Headquarters, U.S. Army Corps of Engineers

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by William W. Walker

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Concord, MA 01742

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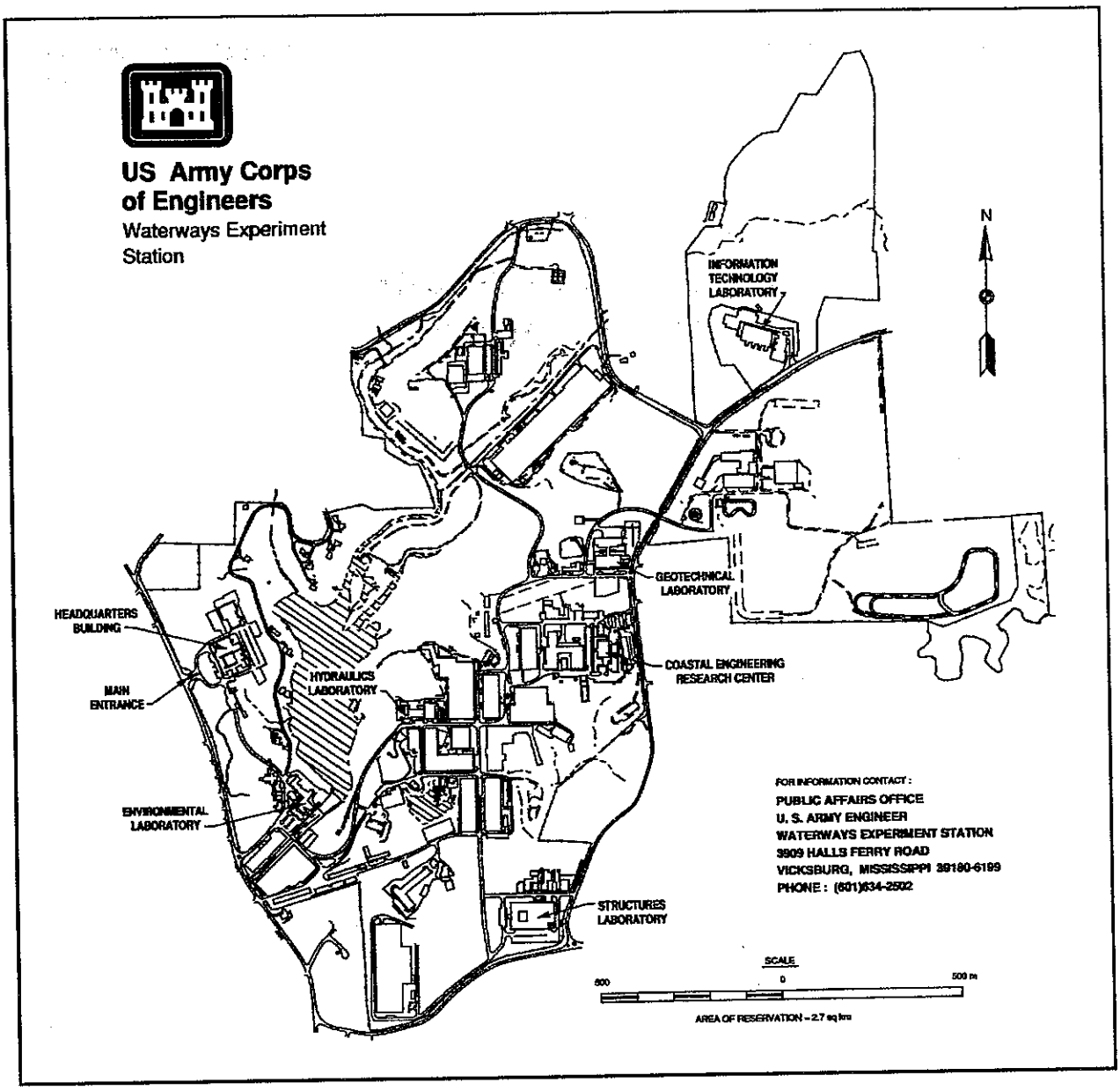

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Contents

Preface vi

1—Introduction 1-1

Background 1-1
Eutrophication Modeling Techniques 1-3
Summary of Assessment Procedures 1-14
Data Requirements 1-18

2—FLUX 2-1

FLUX Overview 2-1
Input Data Requirements 2-2
Theory 2-4
Program Operation 2-14
Typical Application Sequence 2-26
Procedure Outline 2-29
Data-Entry Screens 2-31
Data File Formats 2-33
FLUX Documented Session 2-43

3—PROFILE 3-1

PROFILE Overview 3-1
Input Data Requirements 3-2
Mixed-Layer Water Quality Data Summary 3-4
Oxygen Depletion Calculations 3-7
Program Operation 3-9
Input Data File Format 3-14
Data-Entry Screens 3-19
Documented Session 3-22

4—BATHTUB 4-1

BATHTUB Overview 4-1
Theory 4-2
Program Operation 4-36
Application Steps 4-42
Procedure Outline 4-51
Data-Entry Screens 4-53

Documented Session 4-59
Instructional Cases 4-79

References R-1

Bibliography B-1

Appendix A: Installation A1

Appendix B: Conversion Factors B1

SF 298

List of Figures

Figure 1.1. Control pathways in empirical eutrophication models developed for northern lake applications 1-4

Figure 1.2. Control pathways in empirical eutrophication models developed for CE reservoir applications 1-5

Figure 1.3. Sensitivity analysis of first-order phosphorus sedimentation model 1-12

Figure 1.4. Sensitivity analysis of second-order phosphorus sedimentation model 1-13

Figure 1.5. Assessment pathways 1-15

Figure 1.6. Estimated accuracy of reservoir mean concentration computed from sampling designs with between 1 and 30 sampling rounds over a range of temporal CVs 1-29

Figure 3.1. Sample PROFILE output: Surface water quality summary . . 3-5

Figure 3.2. Example box plot for Beaver Reservoir 3-7

Figure 4.1. Schematic of BATHTUB calculations 4-3

Figure 4.2. Control pathways in empirical eutrophication models developed for CE reservoir applications 4-5

Figure 4.3. BATHTUB segmentation schemes 4-17

Figure 4.4. Mean depth (Z) versus hydraulic residence time (T) for CE model development data set LOG_{10} scales 4-25

Figure 4.5. Relationships between nutrient residence times and hydraulic residence times in CE model development data set 4-27

Figure 4.6. Phosphorus, nitrogen, turbidity relationships for CE reservoirs (nonalgal turbidity calculated as 1/Secchi (m) - 0.025 Chl *a* (mg/m^3)) 4-30

Figure 4.7. Phosphorus, chlorophyll *a*, and transparency relationships for CE reservoirs 4-31

Figure 4.8. Calibration factor for linear phosphorus/chlorophyll model versus light limitation factors 4-34

Figure 4.9. Model segmentation for Lake Keystone, Oklahoma, application 4-59

List of Tables

Table 1.1. Comparison of Lake and Reservoir Empirical Eutrophication Models 1-6

Table 1.2. Mass Balance Terms and Data Sources 1-22

Table 1.3 Minimal and Desirable Designs for Tributary Monitoring Programs 1-23

Table 1.4 General Guidelines for Designing Reservoir Pool Monitoring Programs 1-27

Table 2.1 Estimation Algorithms Used in FLUX Program 2-5

Table 2.2 Stratified Sample Algorithm (Cochran 1977; Bodo and Unny 1983) 2-10

Table 2.3 Breakdown by Flow Stratum - Caddo River Example 2-13

Table 2.4 Typical Application Sequence 2-27

Table 2.5 FLUX File Formats 2-34

Table 4.1 Symbol Definitions 4-6

Table 4.2 BATHTUB Model Options 4-8

Table 4.3 Supplementary Response Models 4-12

Table 4.4 Error Statistics for Model Network Applied to Spatially Averaged CE Reservoir Data 4-13

Table 4.5 Diagnostic Variables and Their Interpretation 4-14

Table 4.6 Equations for Estimating Nonalgal Turbidity, Mixed Depth, and Hypolimnetic Depths in Absence of Direct Measurements 4-33

Preface

The information reported herein is based on a series of technical reports written by Dr. William W. Walker and published by the U.S. Army Engineer Waterways Experiment Station (WES). These previous reports summarized work conducted as part of the Environmental and Water Quality Operational Studies Program, sponsored by the Headquarters, U.S. Army Corps of Engineers (HQUSACE). Preparation of this report was sponsored by HQUSACE, as part of the Water Operations Technical Support (WOTS) Program. The WOTS Program was assigned to WES under the purview of the Environmental Laboratory (EL). Funding was provided under Department of the Army Appropriation 96X3123, Operations and Maintenance. The WOTS was managed under the Environmental Resources Research and Assistance Programs (ERRAP), Mr. J. L. Decell, Manager. Mr. Robert C. Gunkel was Assistant Manager, ERRAP, for the WOTS. Program Monitors for WOTS were Messrs. Frederick B. Juhle and Rixie Hardy, HQUSACE.

The work was conducted under the direct WES supervision of Dr. Robert H. Kennedy, Ecosystem Processes and Effects Branch (EPEB), Environmental Processes and Effects Division (EPED), EL, and the general supervision of Dr. Richard E. Price, Chief, EPEB, Mr. Donald L. Robey, Chief, EPED, and Dr. John W. Keeley, Director, EL.

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1 Introduction

Background

This report describes simplified procedures for eutrophication assessment and prediction. These techniques, initially developed for use at U.S. Army Corps of Engineer (CE) reservoirs, are based upon research previously described in a series of technical reports. These reports describe database development (Report 1; Walker 1981); model testing (Report 2; Walker 1982); model refinement (Report 3; Walker 1985); and applications procedures (Report 4; Walker 1987). Reported here is detailed information concerning application of the latest versions of these techniques using a DOS-based personal computer and also reported is an update of the original applications manual (i.e., Report 4).

Three computer programs facilitate data reduction and model implementation. While the assessment procedures and programs can be "run" based upon the information contained in this report, their intelligent "use" requires an understanding of basic modeling concepts and familiarity with the supporting research. Review of the above research reports and related references on this topic (see References and Bibliography) will facilitate proper use of the techniques described below.

Eutrophication can be defined as the enrichment of water bodies leading to an excessive production of organic materials by algae and/or aquatic plants. This process has several direct and indirect impacts on reservoir water quality and beneficial uses. Common measures of eutrophication include total nutrient concentrations (phosphorus and nitrogen), chlorophyll *a* (a measure of algal density), Secchi depth (a measure of transparency), organic nutrient forms (nitrogen and carbon), and hypolimnetic dissolved oxygen depletion.

The basis of the modeling approach described below is to relate eutrophication symptoms to external nutrient loadings, hydrology, and reservoir morphometry using statistical models derived from a representative cross section of reservoirs. When applied to existing reservoirs, the models provide a framework for interpreting water quality monitoring data and predicting effects of future changes in external nutrient loadings. The models can also be used to predict water quality conditions in a proposed reservoir.

Three basic phases are involved in applying the methodology to an existing or proposed reservoir:

a. Analysis and reduction of tributary water quality data.

b. Analysis and reduction of pool water quality data.

c. Model implementation.

A separate computer program has been developed for each phase. The data-reduction phases are critical steps in the modeling process. The programs can also be used in other aspects of reservoir operation and management, including monitoring program design and generalized data analysis. The model implementation program is designed so that it can be applied to a single reservoir (mixed or spatially segmented), networks of reservoirs (hydrologically linked), or collections of reservoirs (hydrologically independent). The last type of application can support regional comparative assessments of reservoir conditions and controlling factors.

This report is organized in four chapters. Chapter 1 reviews basic empirical modeling concepts, presents an overview of the assessment procedures which have been developed for reservoir application, and summarizes basic data requirements and recommended monitoring strategies. Chapter 2 describes the FLUX program, which is designed for analysis and reduction of tributary monitoring data. Chapter 3 describes PROFILE, a program designed for analysis and reduction of pool monitoring data. Chapter 4 describes BATHTUB, a program designed for model implementation. Appendix A describes the necessary procedures for installing the programs on an IBM-compatible personal computer.

Several levels of involvement are offered to potential users of this methodology. The following steps are suggested:

Step 1: Review summary information (Chapter 1).

Step 2: Review supporting research and basic reference documents.

Step 3: Review program documentation (Chapters 2, 3, and 4).

Step 4: Review documented output listings.

Step 5: Acquire and install programs (Appendix A) on an accessible computer system.

Step 6: Run programs using several sample input files provided.

Step 7: Apply program to user-defined problems.

The above procedures provide a gradual and logical introduction of the techniques and a foundation for their application in a reservoir management context.

Eutrophication Modeling Techniques

Models for reservoir eutrophication can be broadly classified as theoretical or empirical. While all models are empirical to some extent, they are distinguished by their levels of empiricism. General characteristics and limitations of these model types are discussed below.

Theoretical models generally involve direct simulation of physical, chemical, and biological processes superimposed upon a simulation of reservoir hydrodynamics. These methods generally have extensive resource requirements in terms of input data, computing facilities, and user expertise. They can be useful for problems requiring high spatial and temporal resolution and/or simulation of cause-effect relationships which cannot be represented using simpler models. Their relative complexity does not guarantee that simulation models are more accurate or more reliable than simplified models for certain types of applications.

Although based upon theoretical concepts (such as mass balance and nutrient limitation of algal growth), empirical models do not attempt explicit simulation of biochemical processes and use simplified hydrodynamic representations. They generally deal with spatially and temporally averaged conditions. The simple structures, low resolution, limited number of input variables, and initial calibration to data from groups of impoundments result in relatively low data requirements. At the same time, the above characteristics limit model applicability. In one sense, empirical models attempt to "interpolate" the gross responses of a given impoundment, based upon observed responses of other impoundments and levels of certain controlling variables. They also provide a quantitative framework for interpreting monitoring data from a given impoundment and describing eutrophication-related water quality conditions and controlling factors both in absolute and relative terms.

Empirical model structures and evolution

Empirical prediction of reservoir eutrophication can be described as a two-stage procedure involving the following types of models:

a. *Nutrient Balance Models*. These relate pool or discharge nutrient levels to external nutrient loadings, morphometry, and hydrology. (Note that the term "pool" refers to the lake or reservoir impounded by a dam.)

b. *Eutrophication Response Models.* These describe relationships among eutrophication indicators within the pool, including nutrient levels, chlorophyll *a*, transparency, and hypolimnetic oxygen depletion.

Generally, models of each type must be linked to relate external nutrient loadings to reservoir water quality responses. In the absence of loading information, however, application of eutrophication response models alone can provide useful diagnostic information on existing water quality conditions and controlling factors.

The literature contains a wide array of empirical eutrophication models which have been calibrated and tested using data from various lake and/or reservoir data sets. Many of these models, particularly the early ones, were based primarily upon data from northern, natural lakes. While the equations and coefficients vary considerably among the lake models, they share the same sets of variables and basic assumptions, as depicted in Figure 1.1.

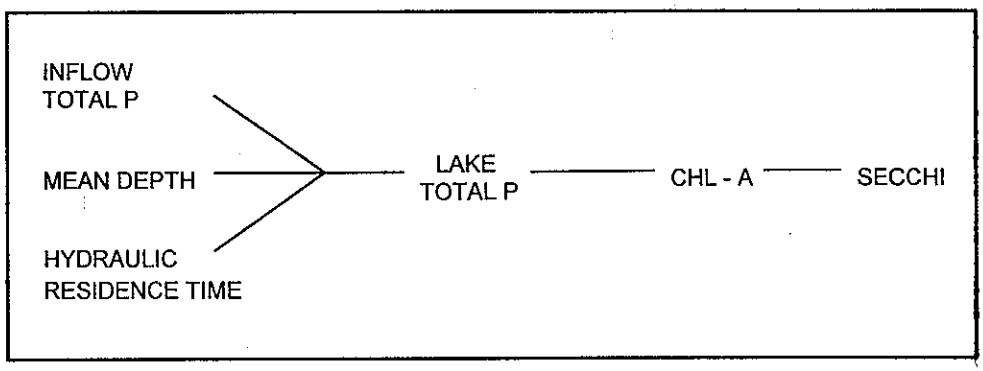


Figure 1.1. Control pathways in empirical eutrophication models developed for northern lake applications

Inputs to these models can be summarized in three terms:

a. Inflow total phosphorus concentration. External loading/discharge rate, a nutrient supply factor.

b. Mean depth. Reservoir volume/surface area, a morphometric factor.

c. Hydraulic residence time. Reservoir volume/discharge rate, a hydrologic factor.

Empirical nutrient balance models have generally evolved from a simplistic "black-box" model which represents the impoundment as a continuous stirred-tank reactor at steady state and the sedimentation of phosphorus as a first order reaction. Phosphorus is assumed to control algal growth and other eutrophication-related water quality conditions. Response models generally consist of bivariate regression equations relating each pair of response measurements (e.g., phosphorus/chlorophyll, chlorophyll/transparency).

In adapting these models for use in CE and other reservoirs (Walker 1981, 1982, 1985), modifications have been designed to include additional input variables, controlling factors, and response variables, as depicted in Figure 1.2. Table 1.1 compares the variables and assumptions of the reservoir models documented in this manual. The reservoir modifications are designed to improve generality by incorporating additional independent variables and controlling factors found to be important in model testing.

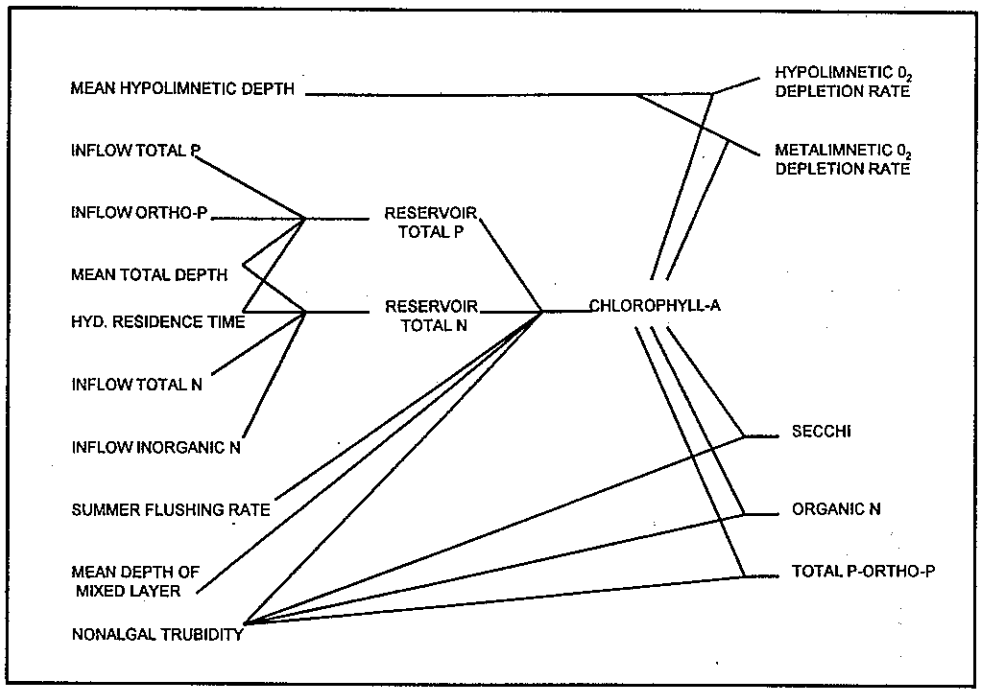


Figure 1.2. Control pathways in empirical eutrophication models developed for CE reservoir applications

Refinements are focused in the following areas:

a. Effects of nonlinear sedimentation kinetics on nutrient balances. A second-order kinetic model appears to be more general than a first-order model for predicting both among-reservoir, spatially averaged variations and within-reservoir, spatial variations.

b. Effects of inflow nutrient partitioning (dissolved versus particulate or organic versus inorganic) on nutrient balances and chlorophyll *a* levels. Because of differences in biological availability and sedimentation rates, reservoir responses appear to be much more sensitive to the ortho-phosphorus loading component than to the nonortho (total minus ortho) component.

Table 1.1
Comparison of Lake and Reservoir Empirical Eutrophication Models

Model Characteristics	Lake Models	Reservoir Models
Input variables	Inflow total P concentration Mean depth Annual hydraulic residence time Mean hypolimnetic depth	Inflow total P concentration Inflow ortho-P concentration Inflow total N concentration Inflow inorganic N concentration Mean depth Mean hypolimnetic depth Mean depth of mixed layer Seasonal hydraulic residence time Nonalgal turbidity
Spatial variability	Mixed	Mixed or spatially segmented
Temporal variability	Steady state	Steady state
Nutrient sedimentation kinetics	Linear (first-order)	Nonlinear (second-order)
Factors controlling algal growth	Phosphorus	Phosphorus Nitrogen Light Flushing rate
Output variables	Total phosphorus Chlorophyll *a* Transparency Hypolimnetic oxygen depletion	Total phosphorus Total nitrogen Chlorophyll *a* Transparency Nonortho-phosphorus Organic nitrogen Hypolimnetic oxygen depletion Metalimnetic oxygen depletion

c. Effects of seasonal variations in nutrient loadings, morphometry, and hydrology on nutrient balances. Pool water quality conditions are related more directly to seasonal than to annual nutrient balances in impoundments with relatively high flushing rates.

d. Effects of algal growth limitation by phosphorus, nitrogen, light, and flushing rate on chlorophyll *a* concentrations. Simple phosphorus/chlorophyll *a* relationships are of limited use in reservoirs because nitrogen, light, and/or flushing rate may also regulate algal growth, depending upon site-specific conditions.

e. Effects of spatial variations in nutrients and related variables, as controlled by reservoir morphometry, hydrology, and the spatial distribution of tributary nutrient loads. Nutrient-balance models can be implemented in a spatially segmented framework which accounts for advection, dispersion, and sedimentation to predict water quality variations among and within major tributary arms. This spatial resolution can be important for evaluating impacts on reservoir uses, depending upon locations of water-use points (e.g., water-supply intakes, bathing beaches, parks, fishing areas, and/or wildlife refuges).

Model structures have been tested against several independent reservoir data sets. Details on model development and testing are described in the supporting research reports (Walker 1982, 1985).

Applications

Potential model applications can be classified into two general categories: diagnostic and predictive. Characteristics and limitations of these applications are described below.

In a diagnostic mode, the models provide a framework for analysis and interpretation of monitoring data from a given reservoir. This yields perspective on eutrophication-related water quality conditions and controlling factors. Assessments can be expressed in absolute terms (nationwide, e.g., with respect to water quality objectives, criteria, or standards) and/or relative terms (e.g., comparisons with other impoundments, or regionally). Using routines and statistical summaries included in the BATHTUB program, observed or predicted reservoir characteristics can be ranked against characteristics of CE reservoirs used in model development.

In a predictive mode, the models are used to project future conditions in either existing or planned reservoirs. The distinction between the two types of predictive applications is important. In the first case, monitoring data from an existing reservoir can be used, in combination with the models and diagnostic analyses, as a "starting point" for "extrapolation" to future conditions. Because of the opportunity for site-specific calibration, projections of future conditions in an existing reservoir are generally subject to less uncertainty than projections of water quality conditions in a proposed reservoir.

In a predictive mode, the models project steady-state responses to changes in controlling variables which are explicitly represented in the model network (Figure 1.2). Such projections can be used in impact assessments and in

evaluations of water-quality-control strategies. For example, future scenarios involving changes in seasonal or annual-mean values of the following factors can be evaluated:

a. Inflow nutrient concentrations or loadings (total phosphorus, ortho phosphorus, total nitrogen, and/or inorganic nitrogen).

b. Pool elevation, as it influences mean depth, mixed-layer depth, mean hypolimnetic depth, and hydraulic residence time.

c. Inflow volume and changes in hydraulic residence time.

d. Pool segmentation, as it influences longitudinal nutrient transport, sedimentation, and the spatial distribution of nutrients and related water quality conditions.

Applications of the first type are of primary importance because control strategies for reservoir eutrophication are usually focused on external nutrient (especially, phosphorus) supplies.

Examples of impacts and control strategies which cannot be explicitly evaluated with these models include the following:

a. Variations in pool level or other model input variables which occur over time scales shorter than the growing season (typically, 6 months).

b. Changes in outlet levels.

c. Structural modifications, such as the construction of weirs.

d. Hypolimnetic aeration or destratification.

e. Other in-reservoir management techniques, including dredging and chemical treatment to control internal nutrient recycling.

In such cases, implementation of the models in a diagnostic mode can provide useful baseline water quality perspectives; however, simulation or other approaches must be used for predictive purposes.

Although the supporting research has focused on reservoirs, the computational framework can also be applied to natural lakes. Certain procedures and concepts are essential to evaluating eutrophication problems in lakes or reservoirs. These include calculation of tributary nutrient loads, summary of observed water quality conditions, construction of water balances, and construction of mass balances. In adapting the empirical lake models (Figure 1.1) for use in reservoirs, the goal has been to increase model generality, so that the resulting formulations can be applied within certain constraints to lakes or to reservoirs. The limits and extent of model testing against lake data sets are summarized in the supporting research reports (Walker 1982, 1985). Options

for implementing empirical models previously developed exclusively from lake data sets are also included in the software.

Error, variability, and sensitivity analysis

The distinction between "error" and "variability" is important. Error refers to a difference between an observed and a predicted mean value. Variability refers to spatial or temporal fluctuations in concentration about the mean. Prediction of temporal variability is generally beyond the scope of empirical modeling efforts, although such variability is important because it influences the precision of observed mean values calculated from limited monitoring data.

Because both measurement and model errors tend to increase with concentration scale, errors are most conveniently expressed on a percentage basis or logarithmic scales. This stabilizes variance over the ranges of concentration encountered, an important requirement for application of common statistical techniques (e.g., regression). This report frequently uses the mean coefficient of variation (CV) as a measure of error. The CV equals the standard error of the estimate expressed as a fraction of the predicted value. For example, a CV of 0.2 indicates that the standard error is 20 percent of the mean predicted value. Assuming that the errors are log-normally distributed about the predicted value, 95-percent confidence limits can be estimated from the following equation:

$$Y_m e^{-2\,CV} < Y < Y_m e^{2\,CV}$$

where

Y_m = predicted mean value

CV = error mean coefficient of variation

Y = 95-percent confidence range for mean value

Magnitudes, sources, and interpretations of error are discussed below.

Error CVs for the reservoir model network (Figure 1.2) are on the order of 0.27 for predicting total phosphorus and 0.35 for predicting mean chlorophyll *a*. According to the above equation, these statistics translate into 95-percent confidence factors of 1.72 and 2.00, respectively. In applying these models in a reservoir management context, limitations imposed by errors of this magnitude are less severe than immediately apparent because of the following factors:

a. *Despite the relatively wide confidence bands, the models explain 91 percent and 79 percent of the observed variances in total phosphorus and chlorophyll a across reservoirs, respectively.* This reflects the relatively wide ranges of conditions encountered and suggests that the models are adequate for broad comparative analyses of reservoir conditions (i.e., ranking).

b. *Error statistics are calculated from "imperfect" data sets.* Errors are partially attributed to random sampling, measurement, and estimation errors in the input and output (i.e., observed) conditions, which inflate the total error but do not reflect model performance.

c. *Error magnitudes refer to predictions which are made without the benefit of site-specific water quality information.* In applications to existing reservoirs, prediction errors can be reduced by calibrating the model (adjusting certain model coefficients) so that predictions match observed water quality conditions. The calibrated model can subsequently be used to project water quality changes likely to result from changes in nutrient loads or other controlling factors.

d. *Year-to-year water quality variations induced by climate, hydrology, nutrient loading, and other factors are substantial in many reservoirs.* It would be difficult to detect modest errors in predicting average conditions without several years of intensive monitoring.

e. *Ability to define objective criteria or standards is limited.* The "penalty" or "risk" associated with modest errors in predicting average responses may be low when expressed in terms of impacts on water uses. The measured and modeled variables (chlorophyll *a*, etc.) are reasonable and practical, but imperfect, surrogates for potential water-use impacts.

f. *Ability to predict changes in loading resulting from adoption of specific management strategies is limited.* This applies particularly to implementation of nonpoint source loading controls with performances evaluated using watershed simulation models. In such situations, errors associated with predicting reservoir response may be swamped by errors associated with predicting loadings; i.e., the reservoir response model may not be the limiting factor in the analysis.

Error-analysis concepts discussed below provide additional perspectives on the above points.

Differences between observed and predicted reservoir conditions can be attributed to the combined effects of a number of error sources, as described below:

a. *Independent variable error.* These are errors in the estimates of model input variables, including external nutrient loadings, flows, and reservoir morphometry.

b. *Dependent variable error.* These are errors in the estimates of mean observed reservoir water quality conditions, based upon limited monitoring data.

c. *Parameter error.* These errors are attributed to biases or random errors in the model coefficients estimated from cross-sectional data sets.

d. *Model error.* These errors are attributed to errors in model structure or effects of factors which are not explicitly represented.

The user has direct control over the first two error sources (i.e., independent and dependent variable error), primarily through design and implementation of appropriate monitoring programs and use of proper data reduction techniques. The last two sources (i.e., parameter and model error) are also under user control to the extent that the user selects the model(s) deemed appropriate for specific application. Research (Walker 1981, 1982, 1985) has been directed at minimizing the last two error sources by reviewing, screening, refining, calibrating, and testing arrays of models which are appropriate for reservoir applications under specific conditions.

The impacts of errors in specifying model input variables or coefficients depend upon the sensitivities of model predictions to those inputs. Sensitivities, in turn, reflect model structure and variable ranges. A sensitivity coefficient can be conveniently expressed as a normalized first derivative, or as the percent change in a model output variable induced by a 1-percent change in a model input. For example, a sensitivity coefficient of 1.0 would indicate that the output is proportional to the input; in this situation, for example, a 5-percent error in specifying the input would propagate through the model and cause a 5-percent error in the predicted output. For a sensitivity coefficient of 0.2, however, a 5-percent input error would cause only a 1-percent output error. Sensitivity coefficients provide insights into which model variables and coefficients are the most important to measure or estimate accurately.

Figures 1.3 and 1.4 display sensitivity coefficients for models predicting mean phosphorus concentrations in reservoirs assuming first- and second-order sedimentation reactions, respectively. In both cases, the output variable is the error term or the ratio of the observed to the predicted mean phosphorus concentration. Input variables used to calculate this ratio include the observed pool concentration, inflow concentration (flow-weighted over all sources), flushing rate (outflow/volume), and sedimentation coefficient.

Sensitivities vary with flushing rate over the approximate range encountered in CE impoundments (median value for reservoirs used in model testing = 7/year. At low flushing rates (or long hydraulic residence times), sensitivities to the sedimentation coefficient and flushing rate are relatively

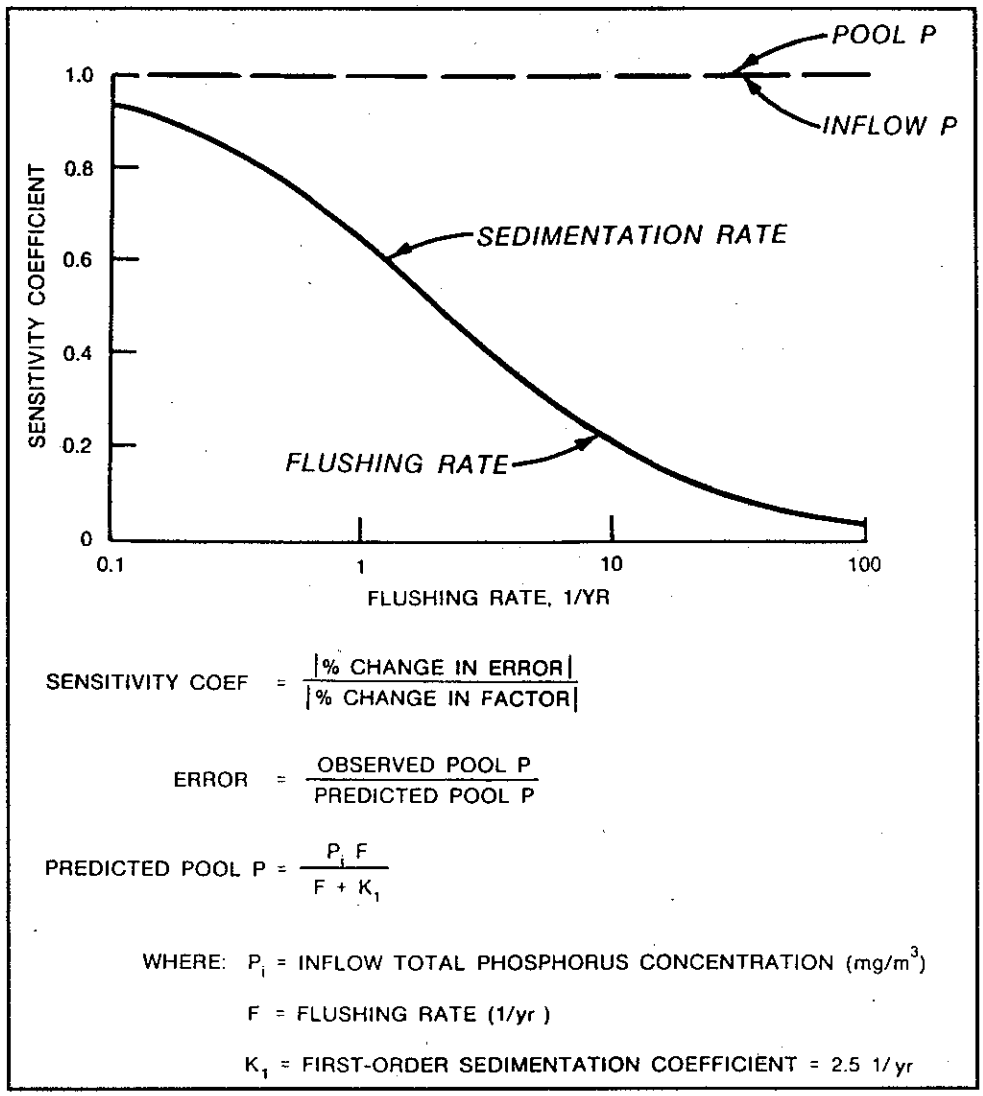
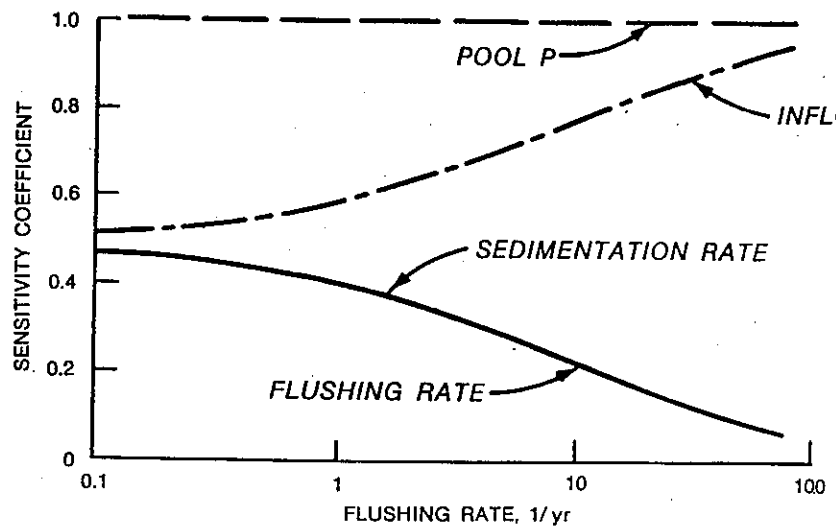


Figure 1.3. Sensitivity analysis of first-order phosphorus sedimentation model

high (approaching 1.0 for the first-order model and 0.5 for the second-order model). This reflects the relative importance of the sedimentation term in the overall phosphorus balance of the reservoir. At high flushing rates, sensitivities to the sedimentation coefficient and flushing rate approach zero for both models. In this situation, the sedimentation process is relatively unimportant, and modest errors in the specified flushing rate and/or sedimentation coefficient can be tolerated without having major impacts on the predicted pool concentration. Because the sedimentation coefficient is estimated from highly simplified empirical models (whereas the other input terms can be directly measured), its sensitivity characteristics have a strong influence on model performance and uncertainty over the range of flushing rates.



$$\text{SENSITIVITY COEF} = \frac{|\%\ \text{CHANGE IN ERROR}|}{|\%\ \text{CHANGE IN FACTOR}|}$$

$$\text{ERROR} = \frac{\text{OBSERVED POOL P}}{\text{PREDICTED POOL P}}$$

$$\text{PREDICTED POOL P} = \frac{-F + \sqrt{F + 4\,P_i\,K_2}}{2\,K_2}$$

WHERE: F = FLUSHING RATE (1/yr)

P_i = INFLOW TOTAL PHOSPHORUS CONCENTRATION = 50 mg/m^3

K_2 = SECOND-ORDER SEDIMENTATION COEFFICIENT = .1 m^3/mg-yr

Figure 1.4. Sensitivity analysis of second-order phosphorus sedimentation model

Figures 1.3 and 1.4 are intended primarily to demonstrate sensitivity analysis concepts. They also illustrate some important basic characteristics of empirical nutrient balance models:

a. Sensitivities are highest for inflow and pool phosphorus concentrations over the entire range of flushing rates. This emphasizes the importance of monitoring programs (tributary and pool) and data reduction procedures to modeling efforts.

b. Because of a higher sensitivity to phosphorus sedimentation, potential prediction errors are greater for reservoirs with lower flushing rates.

While pool nutrient concentrations can be predicted relatively easily from inflow concentrations in reservoirs with high flushing rates, predictions of biological responses (as measured by chlorophyll *a*) may be more difficult because of temporal variability in nutrient levels (induced by storm events, for example) and/or controlling effects of turbidity and flushing rate. The importance of obtaining accurate inflow and pool concentration estimates for model implementation has led to the development of the computer programs described in subsequent chapters. FLUX and PROFILE are designed to make efficient use of tributary and pool monitoring data, respectively, in calculating the required summary statistics.

Summary of Assessment Procedures

Figure 1.5 depicts the basic steps involved in applying the eutrophication assessment procedures described in this and subsequent chapters. The "pathway" comprises four general stages:

a. Problem identification.

b. Data compilation.

c. Data reduction.

d. Model implementation.

Once the user has developed a working understanding of the model structures, assumptions, and limitations by reviewing basic references and supporting research (see References and Bibliography), most of the effort and cost would typically be involved in the data compilation and data reduction stages. Three computer programs have been written to assist at various stages of the analysis. The functions of these programs are outlined below:

a. FLUX - estimation of tributary mass discharges (loadings) from grab sample concentration data and continuous flow records.

b. PROFILE - display and reduction of pool water quality data.

c. BATHTUB - implementation of nutrient balance and eutrophication response models.

Figure 1.5 summarizes the basic inputs, functions, and outputs of each supporting program. This chapter provides an overview of each analytical stage. Details are given in subsequent chapters, along with examples and guidance for use of the computer software.

PATHWAY	PROCEDURES	
PROBLEM DEFINITION	• DESCRIBE RESERVOIR AND/OR WATERSHED CHARACTERISTICS • DEFINE WATER QUALITY MANAGEMENT OBJECTIVES • IDENTIFY IMPACTS/CONTROL STRATEGIES TO BE EVALUATED • DETERMINE STUDY TYPE: DIAGNOSTIC PREDICTIVE • DETERMINE MODEL TYPE: NUTRIENT BALANCE EUTROPHICATION RESPONSE	
DATA COMPILATION	COMPILE TRIBUTARY AND DISCHARGE DATA • HYDROLOGY • WATERSHED CHARACTERISTICS • WATER QUALITY	COMPILE RESERVOIR POOL DATA • HYDROLOGY • MORPHOMETRY • WATER QUALITY
DATA REDUCTION	RUN **FLUX** PROGRAM • DATA ENTRY • DIAGNOSTIC DISPLAYS • DATA STRATIFICATION • LOADING CALCULATIONS ANNUAL SEASONAL	RUN **PROFILE** PROGRAM • DATA ENTRY • DIAGNOSTIC DISPLAYS • OXYGEN DEPLETION CALCULATIONS • MIXED-LAYER SUMMARIES
MODEL IMPLEMENTATION	RUN **BATHTUB** PROGRAM • SEGMENTATION • SUBMODEL SELECTION NUTRIENT BALANCE EUTROPHICATION RESPONSE • DATA ENTRY • CALIBRATION AND TESTING • SENSITIVITY ANALYSIS • ERROR ANALYSIS • APPLICATIONS DIAGNOSTIC PREDICTIVE	

Figure 1.5. Assessment pathways

Problem identification

The problem identification stage defines the scope of the modeling effort. The following factors are specified:

a. The reservoir, watershed, and water uses.

b. Water quality standards and management objectives.

c. Whether the reservoir is existing or planned.

d. Specific management strategies or impacts to be evaluated.

e. Types of evaluations to be performed.

(1) Diagnostic.

(2) Predictive.

f. Classes of models to be used.

(1) Nutrient balance.

(2) Eutrophication response.

If the analysis is not directed toward evaluating specific management strategies or impacts, the general objective may be to develop perspectives on reservoir water quality conditions and controlling factors as part of a "diagnostic" study. This may lead, in turn, to future evaluations of specific management strategies designed for water quality control.

Two general types of evaluations may be performed. In a diagnostic mode, the models are used as a framework for interpreting monitoring data from the reservoir and/or its tributaries. A diagnostic study provides insights into factors controlling algal productivity and rankings of trophic state indicators versus water quality criteria and/or data from other CE reservoirs. In a predictive mode, the models are applied to predict future conditions in a planned reservoir or in an existing reservoir undergoing changes in nutrient loading regime and/or other controlling factors.

Model classes are determined by the types of analyses to be performed. Both nutrient balance and eutrophication response models are required for a predictive analysis. Diagnostic studies of existing reservoirs can be based exclusively upon response models and pool water quality data; this provides a basis for defining existing conditions and controlling factors, but not for evaluating watershed/reservoir or load/response relationships. Monitoring requirements are generally more stringent for implementing nutrient-balance models than for implementing eutrophication-response models.

Response models and pool monitoring data may be used in preliminary diagnostic studies aimed at defining reservoir conditions. In some reservoirs, this may be followed by implementation of a more elaborate monitoring program designed to quantify nutrient loadings and to support nutrient-balance modeling. Priorities can be established based upon the severities of existing eutrophication-related problems (if any), intensities and types of water use, and potential for future improvement or degradation owing to changes in loading regime.

Data compilation

As shown in Figure 1.5 data compilation occurs in two general areas. The reservoir data required for implementation of eutrophication-response models include morphometric characteristics, outflow hydrology, and pool water quality obtained over at least one complete growing season (three preferred). The watershed data required for implementation of nutrient-balance models include basic watershed characteristics (e.g., subwatershed delineations, topography, geology, land uses, point source inventories) and tributary flow and nutrient concentration data taken at reservoir entry points over at least one full water year (three preferred). Details on data requirements and suggested monitoring designs are given later in this chapter.

Data reduction

In the data reduction phase, pool and tributary water quality data are reduced or summarized in forms which can serve as model input. Since the models generally deal with conditions averaged over a growing season within defined reservoir areas (segments), data reduction involves the averaging or integration of individual measurements, sometimes with appropriate weighting factors.

The FLUX program is designed to facilitate reduction of tributary inflow monitoring data and reservoir outflow monitoring data. Using a variety of calculation techniques, FLUX estimates the average mass discharge or loading that passes a given tributary monitoring station, based upon grab-sample concentration data and a continuous flow record. Potential errors in the estimates are also quantified and can be used to (a) select the "best" or least error loading estimate, (b) assess data adequacy, and (c) improve future tributary monitoring efficiency via optimal allocation of sampling effort among seasons and/or flow regimes. Graphic displays of concentration, flow, and loading data are also provided for diagnostic purposes.

The PROFILE program facilitates analysis and reduction of pool water quality data from existing reservoirs. A variety of display formats are provided to assist the user in developing perspectives on spatial and temporal water quality variations within a given reservoir. Algorithms are included for calculation of hypolimnetic oxygen depletion rates and for robust estimation of area-weighted, surface-layer mean concentrations of nutrients and other response measurements used in subsequent modeling steps.

Model implementation

The BATHTUB program applies empirical eutrophication models to morphometrically complex reservoirs or to collections of reservoirs. The program performs water and nutrient balance calculations in a steady-state, spatially segmented hydraulic network which accounts for advective transport,

diffusive transport, and nutrient sedimentation. Eutrophication-related water quality conditions (expressed in terms of total phosphorus, total nitrogen, chlorophyll *a*, transparency, organic nitrogen, particulate phosphorus, and hypolimnetic oxygen depletion rate) are predicted using empirical relationships previously developed and tested for reservoir applications (Walker 1983).

To reflect data limitations or other sources of uncertainty, key inputs to the model can be specified in probabilistic terms (mean and CV). Outputs are expressed in terms of a mean value and CV for each mass balance term and response variable. Output CVs are based upon a first-order error analysis which accounts for input variable uncertainty and inherent model error.

As shown in Figure 1.5, applications of BATHTUB would normally follow use of the FLUX program for reducing tributary monitoring data and use of the PROFILE program for reducing pool monitoring data. Use of the data reduction programs is optional if independent estimates of tributary loadings and/or average pool water quality conditions are used.

Data Requirements

This section summarizes data requirements to support model applications. The following categories are discussed:

a. Watershed characteristics.

b. Water and nutrient loadings.

c. Reservoir morphometry.

d. Pool water quality and hydrology.

Before describing each area in detail, it is appropriate to discuss some general concepts and guidelines that may be helpful in the design of a reservoir study.

In a typical application, most of the effort and cost would be expended in the critical data-gathering phase. Information sources would generally include project design memoranda, basin planning reports, historical hydrologic and water quality data, and water quality data gathered specifically for the study. Data requirements can be given rather explicitly, as determined by the list of model input variables. Specific data sources and monitoring program designs cannot be dictated, however, because they are influenced by unique aspects of each reservoir and its watersheds, the extent of existing data, logistic considerations, and study resources.

Compilation and review of existing data are important initial steps in conducting a reservoir study. Preliminary application of models using existing data (even if inadequate) can highlight data strengths and weaknesses and help

to focus future monitoring activities. In some cases, existing data may be adequate to support modeling efforts. When existing data are inadequate or unavailable, a phased monitoring program is generally indicated. The first phase involves a small-scale program designed to obtain preliminary data for use in designing efficient monitoring programs for subsequent years. A phased study can be a relatively cost-effective means of data acquisition.

Given specific objectives (e.g., quantifying annual total phosphorus load or growing-season mean chlorophyll *a* concentration in an existing reservoir), statistical methods can be applied to improve monitoring efficiency. As the efficiency of a monitoring program increases, the amount of uncertainty (variance) in the measured variable decreases. Monitoring efficiency may be improved by optimizing the allocation of sampling effort, subject to logistic and economic constraints. Examples of such optimization procedures include the following:

a. Allocation of samples among flow regimes to estimate loadings from a given tributary.

b. Allocation of samples among tributaries to estimate total reservoir loading.

c. Allocation of samples among stations, depths, and dates to estimate reservoir-mean concentrations.

Phased studies or useful existing databases are required to implement these optimization procedures. Because of logistic constraints, multiple monitoring objectives, and other factors, "optimal" designs are rarely implemented; instead, they can be used to indicate appropriate directions for adjusting existing sampling designs.

Watershed characteristics

Basic watershed information is used in the development and interpretation of hydrologic and nutrient loading data, in the design of tributary monitoring programs, and in the assessment of problem sources and control strategies. Maps (U.S. Geological Survey topographic or other) are the most useful formats for this type of information. Separate maps (or a series of transparent overlays) can be used to summarize the following types of watershed information:

a. Elevation contours.

b. Subwatershed delineations.

c. Dominant land uses.

d. Soil types.

(1) Hydrologic soil groups.

(2) Erosion potential.

e. Point sources.

f. Monitoring station locations.

Aerial photos, regional planning agencies, design memoranda, Geographic Information System (GIS) databases, and/or published basin reports are generally useful sources of watershed information. Soils information would also be available from the Soil Conservation Service. The information should be summarized in a tabular form by subwatershed.

Land uses, soil types, topography, and point sources are important factors in determining runoff and nutrient export from a given subwatershed. This type of information is used to do the following:

a. Design tributary monitoring programs (place stations).

b. Interpret watershed monitoring data (compare monitored runoff and loads from different subwatersheds to develop perspectives on regional land use/nutrient-export relationships).

c. Estimate loadings from unmonitored watersheds (use land use/nutrient-export factors or proportion monitored loads from a nearby watershed with similar land uses and soil types, based upon drainage area).

Projections of future land use and point-source nutrient loads are also required for predicting impacts of watershed development.

Water and nutrient loadings

The formulation of water and nutrient balances for the reservoir is a critical step in the empirical modeling process. The following components are of concern:

a. Water.

b. Total phosphorus.

c. Ortho phosphorus.

d. Total nitrogen.

e. Inorganic nitrogen (Ammonia + Nitrate + Nitrite).

f. Conservative substance (e.g., chloride).

Water and total phosphorus balances are essential. The other components are optional. While nitrogen balances are desirable, they may be omitted if monitoring data and/or preliminary mass balance calculations indicate that the reservoir is clearly not nitrogen limited under existing and future loading conditions. The ortho-phosphorus and inorganic nitrogen (ammonia, nitrate, and nitrite) loading components are required for (optional) implementation of nutrient sedimentation models which account for the "availability" or partitioning of total nutrient loads between dissolved and particulate (or inorganic and organic) fractions. Conservative substance balances are useful for testing water balances and calibrating diffusive transport rates in segmented reservoirs.

The nutrient species listed above correspond to those monitored by the U.S. Environmental Protection Agency (EPA) National Eutrophication Survey, the primary data source used in model development and testing. Monitoring of other species (particularly, total dissolved phosphorus) may be desirable for defining inflow nutrient partitioning and availability. Because of existing data constraints, however, the models are based upon the above species.

Generally, balances should be formulated over both annual and seasonal (e.g., May-September) time periods. Annual balances should be calculated on a water-year (versus calendar-year) basis. While traditional nutrient loading models deal with annual time scales, seasonal loadings are better predictors of trophic status in many reservoirs. The methodologies presented in subsequent sections can be applied separately to annual and seasonal nutrient balance data. Nutrient residence time criteria are used to assess the appropriate time scale for each reservoir.

The nominal definition of seasonal (May-September) can be adjusted in specific applications, depending upon seasonal variations in inflow hydrology and, especially, pool level. For example, if a full recreational pool were maintained June through August and much lower elevations were maintained during other months for flood control purposes, then a June-August time scale may be more appropriate for seasonal nutrient balances. Generally, seasonal balances are less important in projects with little or no inflow or outflow during the summer months. The formulation of both seasonal and annual balances is generally recommended for all applications and does not substantially increase monitoring requirements, since both sets of loading estimates can be derived from the same monitoring program.

For each component and time scale, a control volume is drawn around the reservoir (or reservoir segment) and the following mass balance terms are quantified:

a. Total inputs.

b. Total outputs.

c. Increase in storage.

d. Net loss.

Table 1.2 outlines the specific elements of each term and general data sources. Since water is conservative, the net loss term in the water balance (estimated by difference) reflects errors in the estimates of the other water balance terms. For nutrients, the net loss term can be estimated by difference or, in a predictive mode, by using empirical nutrient sedimentation models which have been calibrated and tested for reservoir applications.

Table 1.2
Mass Balance Terms and Data Sources

Mass Balance Terms	General Data Sources
Inputs	
Gauged tributaries	Direct monitoring
Ungauged tributaries	Drainage area approximations Watershed models
Direct point sources	Direct monitoring Per capita loading factors
Shoreline septic systems	Per capita loading factors Hydrogeologic studies
Direct groundwater inputs	Hydrogeologic studies
Atmospheric	Local precipitation data Regional atmospheric deposition
Outputs	
Outflows and withdrawals	Direct monitoring
Evaporation	Local climatologic data
Increase in storage	Pool elevation and morphometry data
Net loss	Calculated by difference Represents error in water balance Emperical nutrient sedimentation models

In general, direct monitoring is recommended to quantify major flow and nutrient sources. Table 1.3 summarizes "minimal" and "desirable" designs for tributary monitoring programs and methods for quantifying other loading components. These are intended as general guidelines to be modified based

Table 1.3
Minimal and Desirable Designs for Tributary Monitoring Programs

Feature	Minimal Design	Desirable Design	Comments
Duration of water and nutrient balance monitoring	One water year (October-September) Coupled with pool monitoring	Three water years	Determined partially by extent of year-to-year variability in hydrology and nutrient loadings
Tributary discharge locations	Major flow sources and outflows	All tributaries and outflows	Prioritize based upon watershed size
Tributary discharge frequency	Daily/event based	Continuous monitoring	
Tributary water quality locations	Major load sources and outflows; just upstream of reservoir	All tributaries and outflows	Monitor at least 75 percent of total load Prioritize tributaries with large watersheds, high land use intensity, and/or significant point sources
Tributary water quality components	Instantaneous flow Total and ortho-P Organic and inorganic-N	Add: Total dissolved P Suspended solids	Nitrogen species passed or sampled less frequently if clearly not limiting based upon pool monitoring and/or preliminary nutrient balances
Tributary water quality frequency	Biweekly (nominal) Supplemented with event sampling Monthly for minor load sources	Weekly (nominal) Continuous storm event monitoring Biweekly for minor load sources	Characterize annual and seasonal loadings Adjust frequencies according to relative magnitude (importance) of load, temporal variability in load and flow, flow/concentration dynamics, guidance from FLUX program

(Continued)

Table 1.3 (Concluded)

Feature	Minimal Design	Desirable Design	Comments
Ungauged watersheds/local direct runoff flows and loadings	Account for less than 25 percent of total load Estimate by drainage area proportioning using monitored export rates from regional watersheds with similar land uses and geology	Account for less than 10 percent of total load Supplement with direct runoff monitoring and/or independent watershed modeling	Develop perspectives on runoff rates and concentrations through regional databases
Direct point sources	Estimate from type of source, plant size, treatment process, and literature values for effluent concentrations or per capita loading factors	Source specific 24-hr flow-weighted composites Sufficient samples to characterize seasonal and annual loads	Sampling design should consider effects of daily, weekly, seasonal variations in load from municipal/industrial discharges Monitor directly if significant portion of total load
Shoreline septic tanks	Estimate from use intensity and typical per capita loading factors Adjust according to soil characteristics, design, and maintenance practices	Direct monitoring	Usually unimportant
Atmospheric loading	Use literature values, regional if available	Monitor directly over annual period Capture dry-fall and wet-fall	Usually unimportant except in projects with low surface overflow rates and low tributary inflow concentrations
Groundwater loadings	Site specific Usually insignificant	Site specific Hydrogeologic studies	Usually unimportant Possible significance indicated by errors in water balance
Precipitation and evaporation	Use seasonal and annual precipitation data from nearby weather station Literature values for seasonal and annual evaporation rates	Onsite monitoring Local pan evaporation studies and precipitation gauges	Used in developing water balance Usually insensitive except in projects with low surface overflow rates

upon site-specific conditions. The basic design for major tributaries and outflows consists of continuous flow monitoring and a combination of periodic grab-sampling and event monitoring for concentration. A sampling program weighted toward high-flow regimes is generally desirable for estimation of loadings. The multiple objectives of estimating both annual and seasonal loadings should be considered in designing surveys. The FLUX program can be applied to historical and/or preliminary monitoring data to assist in sampling design.

While balances are formulated for the study (monitored) period, a historical hydrologic record is desirable to provide perspective on study conditions in relation to long-term averages and extremes. Long-term hydrologic records are usually available for reservoir discharge sites and major tributary inflows. If not, records from a nearby, long-term station, possibly outside the watershed(s), can be correlated with monitoring data from study sites and used to extrapolate the record.

Reservoir morphometry

Reservoir morphometric information is required for nutrient balance and eutrophication response models. It is usually readily available from project design memoranda and other sources. A map indicating the following basic information is useful:

a. Distance scale.

b. Shoreline for typical and extreme pool levels.

c. Bottom elevation contours or soundings.

d. Tributary inflows and any direct point sources.

e. Pool and tributary monitoring station locations.

The following morphometric data should also be compiled in tabular form:

a. Elevation/area volume table.

b. Typical operating pool elevations (rule curve).

c. Reservoir bottom elevation at each pool sampling station.

d. Volumes, surface areas, and lengths of major reservoir segments at typical operating elevations.

This information is used in data reduction (PROFILE) and modeling (BATHTUB).

Pool water quality and hydrology

In studies of existing reservoirs, pool water quality and hydrologic data are used for the following purposes:

a. Assessing trophic state, related water quality conditions, and controlling factors.

b. Model testing and calibration.

Expressed in terms of model variables, the primary objectives of the monitoring program are to obtain the data required for calculation of growing-season, mixed-layer, average concentrations of the following variables:

a. Total phosphorus.

b. Dissolved ortho-phosphorus.

c. Total nitrogen.

d. Total inorganic nitrogen.

e. Organic nitrogen.

f. Chlorophyll *a* (corrected for phaeophytin).

g. Transparency (Secchi depth).

f. Conservative substance.

In stratified reservoirs, another primary objective is to estimate hypolimnetic and metalimnetic oxygen depletion rates. Secondary objectives are to develop perspectives on spatial variations, vertical stratification, basic water chemistry, and other variables which are directly or indirectly related to eutrophication.

General guidelines for designing pool monitoring programs are outlined in Table 1.4. Basic design features include component coverage, station locations, sample depths, temporal frequency, and duration. An appreciation for spatial and temporal variability of conditions within the reservoir may be obtainable from historical data and can be very useful in designing future surveys.

The objectives of identifying spatial gradients and calculating reservoir-mean conditions suggest somewhat different emphasis for station placement. Generally, horizontal variations parallel to the net advective flow along the main axis of a major tributary arm are much more important than variations perpendicular to the flow. If they exist, longitudinal gradients in nutrients, algal biomass, and transparency are usually steepest in upper pool areas; this suggests that stations should be more closely spaced in upper pool areas to

Table 1.4
General Guidelines for Designing Reservoir Pool Monitoring Programs

Feature	Minimal Design	Desirable Design
Water quality components	Temperature Total P Organic N Nitrite-Nitrate N Alkalinity Conductivity Dissolved Oxygen Ortho-P Ammonia N Transparency pH Turbidity Chlorophyll *a* (corrected for Phaeophytin) Dominant algal types	Add: Total Silica Total Iron True Color Total Organic Carbon Total Manganese Sulfides Suspended Solids (total and organic) Oxidation reduction potential Algal cell counts (ASU) by type
Station locations	Minimum of three stations/reservoir (near-dam, midpool, upper-pool) Distributed along thalweg of each major tributary arm in representative areas Maximum distance between stations along thalweg = 20 km	Add stations in smaller tributary arms and embayments Critical reservoir use areas Above and below junctions of tributary arms Maximum distance between stations along thalweg = 10 km
Duration of sampling	One growing season (typically April-October) Bracket stratified period, including one round each during spring and fall isothermal periods	Three growing seasons
Frequency - laboratory samples	Monthly or biweekly	Biweekly or weekly
Depths - laboratory samples	Mixed-layer composite Depth-integrated hose sampling	Unstratified reservoirs: surface, mid-depth, and 1 m off bottom Stratified reservoirs: 3 samples in mixed layer 1 sample in thermocline 3 samples in hypolimnion 1 m from top of hypolimnion mid-depth 1 m off bottom
Frequency - field profiles Unstratified reservoirs: Temperature Dissolved oxygen	Unstratified reservoirs: same as laboratory samples Stratified reservoirs: biweekly in spring to early summer (until onset of anoxia), then monthly	Unstratified reservoirs: same as laboratory samples Stratified reservoirs: weekly in spring to early summer (until onset of anoxia), then biweekly
Depths - field profiles Temperature Dissolved oxygen	1-m intervals, top to bottom	Increase spatial frequency in thermocline and other zones with steep gradients
Reservoir hydrology Surface elevation Outflow volumes	Month-end values Monthly totals	Daily values Daily totals

permit adequate resolution of gradients. Most of the reservoir volume, however, is usually located in the lower pool areas, where width and depth tend to be greater and spatial gradients tend to be less pronounced; this suggests a greater emphasis on lower pool stations for the purposes of calculating reservoir means. Because of these trade-offs, it is difficult to use a statistical approach for optimizing station placement within a given reservoir.

Given multiple sampling objectives, a reasonable design rule is to distribute stations throughout representative areas of the reservoir. The size, morphometric complexity, and loading distribution of a reservoir largely determine the required number of stations. A minimum of three stations (upper-pool, midpool, and near-dam) are recommended for small projects with simple morphometry. Based upon reservoir morphometric information, weighting factors can be applied to data from each station in calculating area-weighted reservoir means (see PROFILE).

To provide bases for characterizing variability and developing robust statistical summaries, surveys should be designed to provide replication (some overlap in information content) of measurements made in each reservoir area or segment during each sampling round. There are several ways in which replication can be built into survey designs, including the following:

a. Multiple sampling at a given date, station, and depth.

b. Multiple sampling with depth within the mixed layer at a given date and station.

c. Multiple sampling stations within a given reservoir segment or area.

d. High temporal sampling frequencies, permitting aggregation of data from adjacent sampling dates.

In designing surveys, combinations of the above strategies can be employed to provide data which include at least three measurements for each reservoir segment and sampling round. In the "desirable" design (see Table 1.4), three samples are suggested within the mixed layer for each station and date. Since the stratum is mixed, on the average, the three samples can be treated as replicates. Other strategies listed above can be used in conjunction with depth sampling to provide replication. Another monitoring objective is to sample each station on each sampling round; this greatly simplifies reduction of the data and error analysis, as implemented in the PROFILE program.

Assuming representative station distribution and proper sampling and analytical techniques, the "precision" of a mean, surface-layer, growing-season value depends largely upon the number of sampling rounds and the inherent temporal variabilities of water quality components in the reservoir being studied. For sampling periods of roughly a week or longer, the variance of the mean is roughly inversely proportional to the number of rounds. Based upon

analyses of variance applied to model development data sets (Walker 1980, 1981), temporal variance components of phosphorus, transparency, and chlorophyll *a* are typically 0.31, 0.33, and 0.62, respectively, expressed as CVs. Figure 1.6 shows the estimated accuracies of reservoir mean concentrations computed from sampling designs with between 1 and 30 sampling rounds over a range of temporal CVs. The "value" of each additional round, as measured by the reduction in the mean CV, decreases as the total number of rounds increases. This figure provides a rough perspective on design sensitivity and a basis for interpreting the reliability of data from historical monitoring activities, provided the sampling regimes were both specified and representative.

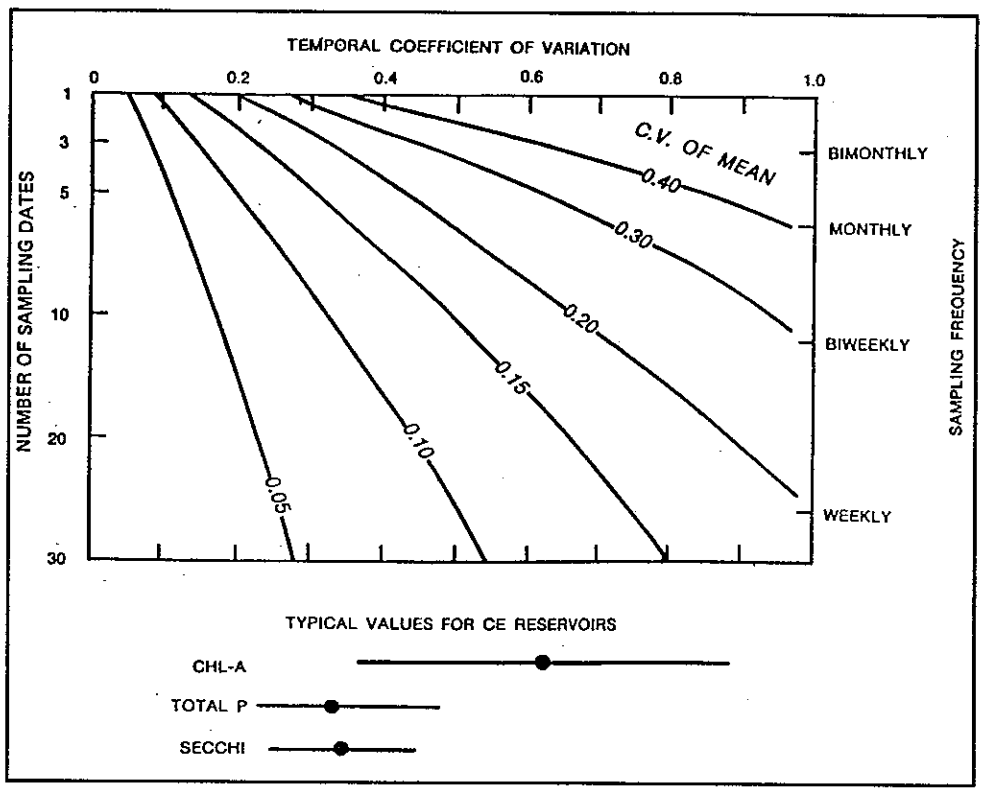


Figure 1.6. Estimated accuracy of reservoir mean concentration computed from sampling designs with between 1 and 30 sampling rounds over a range of temporal CVs

The "adequacy" of a given monitoring program is partially determined by the precision of the mean concentration estimates calculated from the data. Because of the limited pool sampling schedule employed by the EPA National Eutrophication Survey (three to four sampling rounds per growing season), typical error CVs were on the order of 0.18 for mean total phosphorus, 0.18 for mean transparency, and 0.28 for mean chlorophyll *a*. More precise estimates (e.g., mean CVs less than 0.10 for nutrients and transparency and 0.15 for mean chlorophyll *a*) are desirable for model applications in a reservoir management context.

The purpose of sampling in and below the thermocline (Table 1.4) is to provide information on vertical stratification and the accumulation and transformation of nutrients within the hypolimnion. Many important secondary water quality effects of eutrophication are expressed in bottom waters, including oxygen depletion, development of reducing conditions, nutrient accumulation, iron and manganese releases, and sulfide and ammonia generation. While nutrient data from the hypolimnion are not used exclusively in the models, they are important for developing an understanding of nutrient cycling and reservoir processes. Since metalimnetic and hypolimnetic samples are less important for trophic state assessment and model implementation, however, sampling frequencies in and below the thermocline can be lower than those used for the mixed layer.

2 FLUX

FLUX Overview

FLUX is an interactive program designed for use in estimating the loadings of nutrients or other water quality components passing a tributary sampling station over a given period of time. These estimates can be used in formulating reservoir nutrient balances over annual or seasonal averaging periods appropriate for application of empirical eutrophication models. Data requirements include (a) grab-sample nutrient concentrations, typically measured at a weekly to monthly frequency for a period of at least 1 year, (b) corresponding flow measurements (instantaneous or daily mean values), and (c) a complete flow record (mean daily flows) for the period of interest.

Using six calculation techniques, FLUX maps the flow/concentration relationship developed from the sample record onto the entire flow record to calculate total mass discharge and associated error statistics. An option to stratify the data into groups based upon flow, date, and/or season is also included. In many cases, stratifying the data increases the accuracy and precision of loading estimates. Uncertainty is characterized by error variances of the loading estimates. A variety of graphic and tabular output formats are available to assist the user in evaluating data adequacy and in selecting the most appropriate calculation method and stratification scheme for each application. FLUX provides information which can be used to improve the efficiencies of future monitoring programs designed to provide data for calculating loadings and reservoir mass balances.

The succeeding sections of this chapter contain descriptions of the following topics:

a. Input data requirements.

b. Theory.

c. Program operation.

d. Typical application sequence.

e. Procedure outline.

f. Data-entry screens.

g. Data file formats.

h. Documented session.

Input Data Requirements

Two data sets are required to run FLUX. One defines sample characteristics (date of collection, concentration, and instantaneous flow). The other describes the complete flow record (date, mean daily flow) over the period of interest. Most of the effort in applying FLUX is generally involved in setting up the required data files. To facilitate this effort, FLUX can read files in a variety of formats, as described in a subsequent section (see Data file formats).

The function of the program is to use the water quality information in the sample data set to estimate the mean (or total) loading which corresponds to the complete flow distribution over the period of interest. All program calculations and output are in metric units, with flows expressed in million cubic meters (= cubic hectometers, hm^3) per year, concentration in milligrams per cubic meter (parts per billion), and loading in kilograms per year. The data can be stored in other units and converted to the appropriate units when accessed by FLUX (see Appendix B). For a typical nutrient-balance study, sample data sets would include the following components: instantaneous flow, total phosphorus, ortho-phosphorus, total nitrogen, inorganic nitrogen, and a conservative substance such as chloride. Potential applications of the program are not restricted to these constituents, however.

The sample data are normally derived from periodic grab-sampling. Flow measurements stored with the water quality data should correspond to the times of sampling. Daily mean flows can be used in the absence of instantaneous flow measurements; FLUX can automatically pair sample concentrations with corresponding daily mean flows specified in the complete flow record. Generally, samples are collected periodically (weekly to monthly) over a year and over a range of flow regimes. If intensive storm-event monitoring has been conducted, resulting discrete or composite samples should be summarized before they are accessed by FLUX; in this case, each record in the sample data set includes an event mean flow and a flow-weighted mean concentration for each component. Differences in the duration of composite samples are not considered in the current version of FLUX. If continuously sampled events represent a significant fraction of the total loading over the estimation period, the program may overestimate the error variance of the loading estimates. To avoid severe biases in the load estimates, special

consideration must be given to the specification of sample flows in small, flashy streams or storm sewers (see Typical application sequence).

The reliability of loading estimates strongly reflects monitoring program designs. Water quality samples should be taken over the ranges of flow regime and season which are represented in the complete flow record. For a given number of concentration samples, loading estimates will usually be of greater precision if the sampling schedule is weighted toward high-flow seasons and storm events, which usually account for a high percentage of the annual or seasonal loading. While the calculation methods described below are designed to make efficient use of the available data, they cannot work miracles. If the basin dynamics are such that annual loadings are dominated strongly by a few extreme events, no calculation procedure will give an acceptable answer without representative samples from at least some of the major events. FLUX provides graphic and tabular output which can help to evaluate the adequacy of the sample data set for use in load calculations.

Sample data files can include up to 64 fields representing different water quality components and other sample descriptors. Loading calculations are performed for only one component at a time. Concentrations which are entered as zero or negative values are assumed to be missing. Sample records with zero or negative flow values are not used in load calculations. All FLUX calculations are performed in computer memory; source data files are not modified.

The flow data set specifies the complete flow distribution, which is generally derived from continuous stage or velocity measurements made at or near the water quality monitoring site. Typically, flow records consist of a mean flow for each day in the period of interest. In the absence of daily measurements, other averaging flow periods can also be used (weekly, monthly), but with some loss of accuracy. If a continuous flow record is not available for a particular site, one might be constructed using simulation techniques or correlating available flow measurements with simultaneous data from a nearby benchmark station with a continuous flow record and similar watershed.

Missing values are permitted in the flow distribution file, but they should be avoided by estimating them independently. Zero flow values are acceptable to permit applications to intermittent streams. Negative flow values (reverse flows) are treated as zeros. Average flow rates and loads calculated by FLUX reflect total transport in the downstream direction. This may be different from the net transport estimates appropriate for use in BATHTUB or other mass-balance models. If the stream contains significant reverse flows, an option is available for calculating total transport in the upstream direction; this essentially involves reversing the sign of the sample flow and daily flow data. The net downstream transport can subsequently be calculated by subtracting the total upstream transport rates from the total downstream transport rates.

It is convenient to define the time period represented in the sample data set as the "sampling period" and that represented in flow data set as the "averaging period." Normally, these two periods correspond, i.e., the flow data set contains a mean daily flow value for each day in the year of water quality sampling. If the sampling and averaging periods do not correspond (e.g., the sample set might contain data from 1978 through 1981, and the flow set might contain daily flows for 1981), then the user is making the assumption that the flow/concentration dynamics of the stream are stable, i.e., that concentrations measured between 1979 and 1980 are also representative of those measured in 1981. Using samples from outside the averaging period can increase the accuracy and precision of the loading estimates (by increasing the number of samples and improving the coverage of flow regimes); this may introduce bias in the loading estimates, however, if there are significant year-to-year variations in the flow/concentration relationship caused by variations in climate, hydrology, or watershed land use. In each program run, the user specifies the date ranges and/or season ranges to be used for samples and flows; this permits estimation of both annual and seasonal loadings from source data files containing data from 1 or more years of monitoring.

The flow data set may include daily flows from the year(s) of water quality monitoring, as well as other periods which may represent "low-flow," "average," and "high-flow" years. Provided that a sufficiently wide range of flow regimes are sampled, this permits extrapolation of the sample record, i.e., estimation of year-to-year variations in loadings based upon sample data from a specific year or years.

FLUX can handle problems containing up to 500 samples and 7,000 daily flow records (~19 years). These constraints apply to data read into computer memory at the start of program execution, not the size of the input data files. Since the user is prompted for the ranges of sample and flow dates to be used in a given run, the input data files can be much larger than indicated above. Users should check the online documentation file (accessed through the HELP option of the main menu) for maximum problem dimensions and other program changes in updated versions of FLUX (Version 4.5 is documented here).

Theory

Loading calculation methods

Table 2.1 lists the equations used to calculate the mean loading and error variance using six alternative methods. Method applicability depends upon flow/concentration dynamics and sampling program design in each application. Walker (1981,1987) provides details on the derivation and testing of each method. The FLUX procedure "Calculate/Loads" provides a one-page summary of loadings calculated using each method. The user must decide which method is most appropriate for each application, based upon factors discussed below. In most cases, particularly if the data are properly stratified (see Data

Table 2.1
Estimation Algorithms Used in FLUX Program

Method 1 - Direct Mean Loading

W_1 = Mean(w)

Method 2 - Flow-Weighted Concentration (Ratio Estimate)

$W_2 = W_1$ Mean(Q)/Mean(q)

Method 3 - Modified Ratio Estimate (Bodo and Unny 1983)

$W_3 = W_2(1 + F_{wq}/n)/(1 + F_q/n)$

Method 4 - Regression, First-Order (Walker 1981)

$W_4 = W_1[\text{Mean}(Q)/\text{Mean}(q)]^{b+1}$

Method 5 - Regression, Second-Order (Walker 1987)

$W_5 = W_4(1 + r F_Q)/(1 + r F_q)$

Method 6 - Regression Applied to Individual Daily Flows

$W_6 = \Sigma_j \exp [a + (b+1)\ln(Q_j) + SE^2/2]$

where

c_i	=	measured concentration in sample i (mg/m^3)
q_i	=	measured flow during sample i (hm^3/year)
b	=	slope of ln(c) versus ln(q) regression
a	=	intercept of ln(c) versus ln(q) regression
w_i	=	measured flux during sample i = $q_i c_i$ (kg/year)
F_{wq}	=	Cov(w,q) / [Mean(w) Mean(q)]
F_q	=	Var(q) / [Mean(q) Mean(q)]
F_Q	=	Var(Q) / [Mean(Q) Mean(Q)]
Q_j	=	mean flow on day j (hm^3/year)
n	=	number of samples (i)
N	=	number of daily flows (j)
W_m	=	estimated mean flux over N days, method m (kg/year)
V_m	=	variance of estimated mean flux, method m $(kg/year)^2$
r	=	0.5 b (b + 1)
Σ_j	=	sum over N dates in daily flow record
SE	=	standard error of estimate for ln(c) versus ln(q) regression
Mean(x)	=	mean of vector x
Var(x)	=	variance of vector x
Cov(x,y)	=	covariance of vectors x and y

stratification), the calculation methods will give estimates which are not significantly different from each other. Thus, the choice of method will not be critical.

Desired properties of the loading estimates include minimum bias and minimum variance. The distinction between bias and variance (analogous to "accuracy" and "precision") is important. A biased procedure will give the wrong answer, even for an infinite number of samples, whereas variance in the mean can generally be reduced by increasing the number of independent random samples. The seriousness of bias depends upon its size relative to the variance of the mean or the standard error of estimate. Biases less than 10 percent of the standard error account for less than 1 percent of the total mean squared error and are generally considered negligible (Cochran 1977). Bias in a loading estimate can come from two sources: unrepresentative sampling or the use of an inappropriate calculation method. These sources are discussed below.

Consistent problems with sample collection, handling, and analytical procedures can cause one type of unrepresentative sampling; there is little that can be done about these problems at the calculation stage. Another, more subtle, but generally more common type of unrepresentative sampling results from differences in the distributions of flows between the sampling dates and the entire averaging period. Sampled flows may tend to be higher or lower, on the average, than the complete distribution of flows or contain a higher or lower percentage of extreme flows. This can lead to bias in the estimate if the calculation procedure does not take the relative flow distributions into consideration by directly representing the flow/concentration relationship and/or by stratifying the sample, as described below.

Even if the sampled and total flow distributions are equivalent, bias can be introduced as a result of the calculation method. For example, loading calculated as the product of the mean sample concentration and the mean flow over the averaging period would be badly biased if flow and concentration are (even weakly) correlated (Walker 1981). Because of the potential bias associated with this method, it is not included in the program. The six included methods have been selected and tested so that, for representative samples, they should not introduce significant bias except under special conditions discussed below for each method. The extent to which the methods can minimize variance in the loading estimates is limited ultimately by the sample data sets.

Method applicability depends upon the relationship between concentration and flow. In FLUX, this characteristic is represented by the slope of a log(Concentration) versus log(Flow) regression (C/Q slope) derived from the sample data set. Typically, the C/Q slope approaches -1 at monitoring stations which are downstream of major point sources. The slope may approach or exceed 1 at monitoring stations where the load is generated as a result of runoff or high-flow events, particularly for particulate components. In many watersheds, the C/Q slope for total phosphorus varies with flow (negative at

low flows to positive at high flows). FLUX graphic and tabular output helps to characterize the concentration/flow relationship; this characterization is essential to selecting the appropriate calculation method and developing reliable loading estimates.

Method 1 (direct load averaging) is the simplest of the calculation schemes. It gives unbiased results only if the samples are taken randomly with respect to flow regime. This method completely ignores the unsampled flow record and generally has higher variance than the other methods because the flow record on the unsampled days is not considered. This method is most appropriate for situations in which concentration tends to be inversely related to flow (C/Q slope approaching -1; loading does not vary with flow). This might occur, for example, at a station which is below a major point source and the flow/concentration relationship is controlled by dilution.

Method 2 bases the loading estimate on the flow-weighted average concentration times the mean flow over the averaging period. This amounts to a "ratio estimate" according to classical sampling theory (Cochran 1977). This method performs best when flow and concentration are unrelated or weakly related. Some bias may occur for extreme flow/concentration relationships. In test simulations of a stream with a C/Q slope 0.75, Method 2 overestimated loadings by an average of 10 percent (Walker 1987). This bias can be substantially reduced by stratifying the samples into groups of relatively homogeneous concentration and applying the method separately to each group, as described in more detail below. This is perhaps the most robust and widely applicable method, especially when applied to stratified data sets.

Method 3 modifies the Method 2 estimate by a factor that is designed to adjust for potential bias in situations where concentration varies with flow. The factor was developed by Beale (1962) and applied in a load estimation method developed by the International Joint Commission (IJC) (1977), as described by Bodo and Unny (1983, 1984). Trial simulations indicate that, compared with Method 2, this procedure is moderately successful at reducing bias but tends to have slightly higher mean squared error for streams with C/Q slopes greater than or equal to zero (Walker 1987).

Method 4 is the regression method developed by Walker (1981). This method adjusts the flow-weighted mean concentration for differences between the average sampled flow and the average total flow using the C/Q slope. It should not be used in cases where the daily flow data set contains a significant number of zero flow values. This method performs well over a range of C/Q slopes. Some bias is introduced at high C/Q slopes. At a slope of 0.75, for example, simulated bias is 13 percent of the mean loading but accounts for only 6 percent of the total mean squared error (Walker 1987). Additional simulations indicate that bias also occurs if the C/Q slope is highly nonlinear (i.e., quadratic or higher order polynomial). This problem can be resolved by stratifying the sample so that the relationship is approximately linear within each group.

Method 5 modifies the Method 4 estimate by a factor accounting for differences in variance between the sampled and total flow distributions (Walker 1987). The derivation of the method is based upon expected value theory (Benjamin and Cornell 1970). Method 5 should not be used in cases where the daily flow data set contains a significant number of zero flow values. As for Method 4, bias resulting from nonlinearity in the log (c) versus log (q) relationship can be reduced by stratifying the data.

Method 6 is another regression-based calculation method. For each stratum, the C/Q regression equation is applied individually to each daily flow value. In contrast, Methods 4 and 5 use only the flow means and variances. A small correction for bias resulting from the log transformation is also included. This method is often appropriate for generating daily, monthly, or yearly load time series using an optional FLUX procedure designed for this purpose (**Calculate/Series**). Relatively intensive sample data sets and well-defined concentration/flow relationships are required for reliable application of this method. Method 6 is generally preferred over the other regression-based methods when the flow/concentration relationship is well defined. In applications to small, flashy streams, special consideration must be given to the specification of sample flows to avoid bias in Method 6 estimates (see Typical application sequence). Error analysis calculations are time-consuming relative to the other methods. An option to turn off the error analysis for Method 6 is included (**Utilities/Set/Method 6**).

For each method, the jackknife procedure (Mosteller and Tukey 1978) is used to estimate error variance. This involves excluding each sampling event, one at a time, and recalculating loadings, as described in Table 2.2. While alternative, direct estimators of variance are available from classical sampling theory for most of the methods (Cochran 1977; Walker 1981; Bodo and Unny 1983, 1984), such formulas tend to rely upon distributional assumptions. The direct estimators are generally applicable to large samples and normal distributions, neither of which is typical of this application. As described by Cochran (1977), the jackknife has improved properties for ratio estimators derived from small, skewed samples. Use of the jackknife procedure also provides a uniform basis for comparing calculation methods with respect to estimated variance.

Simulations (Walker 1987) indicate that jackknifing provides a reasonably unbiased estimate for error variance for a range of C/Q slopes. Two important factors should be considered in interpreting the variance estimates. First, the estimates are themselves subject to error and are of limited accuracy in small sample sizes, particularly if the sampled flow distribution is not representative. Second, the variance estimates do not reflect effects of biases associated with some calculation methods under certain conditions, as discussed above. Thus, while the estimated variances are important factors to consider in selecting the "best" loading estimation method, the sample characteristics and bias potential should also be considered. FLUX diagnostic procedures assist in this process, as described below.

Error variance estimates developed by FLUX assume that the samples are statistically independent. This may not be the case if the file contains large numbers of discrete samples taken within relatively short periods of time. One approach to solving this problem is to composite the samples by event prior to calculating loadings. Important information on the flow/concentration relationship may be lost in compositing, however. As an alternative to compositing, discrete samples can be grouped by event only for the purposes of error analysis. In FLUX, sampling events are defined by the program parameter T_e = Maximum Event Duration (days). Samples collected within T_e days of each other are considered part of the same sampling event. The default setting for T_e is 1 day. This setting only influences the error variance estimates (not the mean loading estimates). It only influences error variance estimates developed from relatively intensive sample data sets containing multiple samples on the same day or within the current N_d setting.

Data stratification

FLUX includes an option to divide the input flow and concentration data into a series of groups and calculate loadings separately within each group using the methods described above. Using formulas derived from classical sampling theory (Cochran 1977), the mean and variance estimates within each group are subsequently combined across groups using weighting factors which are proportional to the frequency of each group in the total flow distribution (see Table 2.2).

The groups, or "strata," can be defined based upon flow, season, and/or date. Stratification can serve three basic functions:

a. Adjust for differences in the frequency distributions of sampled and unsampled flow regimes.

b. Reduce potential biases associated with some calculation methods and/or sampling program designs.

c. Reduce the error variance of the mean loading estimate.

When sample data are adequate, stratification can offer significant advantages over the direct methods and provide insights that can be used to improve sampling efficiency in future years.

In most applications, the groups are defined based upon flow. The "flow-interval" method was developed by the U.S. Army Engineer District, Buffalo (1975), for use in the Lake Erie Wastewater Management Study and is described by Verhoff, Yaksich, and Melfi (1980) and Westerdahl et al. (1981). This procedure applies the direct load averaging (Method 1) separately to different data groups, defined based upon flow regimes. Since loading usually increases with flow, grouping the data based upon flow reduces the

Table 2.2
Stratified Sample Algorithm (Cochran 1977; Bodo and Unny 1983)

Definitions:

s	=	subscript indicating stratum
m	=	subscript indicating estimation method
N_s	=	number of daily flows in stratum s
N_t	=	total number of daily flows
$n_{s,*}$	=	optimal number of samples in stratum s, given n_t
n_t	=	total number of sampled concentrations
$W_{m,s}$	=	mean flux in stratum s estimated by method m
$V_{m,s}$	=	variance of mean flux in stratum s estimated by m
$S_{m,s}$	=	effective standard deviation within stratum s for method m
$W_{m,t}$	=	mean flux over all strata estimated by method m
$V_{m,t}$	=	variance of mean flux over all strata estimated by method m
$V_{m,t}^*$	=	variance of mean flux over all strata estimated by method m for optimal allocation of n_t samples according to $n_{s,*}$
Σ	=	sum over all strata (s)

Equations:

N_t	=	ΣN_s
n_t	=	Σn_s
$W_{m,t}$	=	$\Sigma (W_{m,s}N_s)/N_t$
$V_{m,t}$	=	$\Sigma (V_{m,s}N_s^2)/N_t^2$
$S_{m,s}$	=	$[n_s V_{m,s}]^{0.5}$
$n_{s,*}$	=	$n_t N_s S_{m,s} / \Sigma (N_s S_{m,s})$
$V_{m,t}^*$	=	$\Sigma (V_{m,s}N_s^2 n_s/n_{s,*})/N_t^2$

loading variance within each group and results in lower variance for the total loading estimate. A flow-stratified version of Method 2 written in SAS (Statistical Analysis System) was developed and applied to estimate phosphorus loadings in a Vermont lake study (Walker 1983). The IJC method described by Bodo and Unny (1983, 1984) is a flow-stratified version of Method 3.

In FLUX, data groups or strata can be defined based upon flow range, date range, and/or season range. Generally, flow ranges would be used and the data would be stratified into two or three groups based upon flow. In some

situations, however, it may be desirable to stratify based upon sampling date or season. Stratification based upon season may be useful in situations where there is a strong seasonal variation in concentration which is independent of flow or for streams with highly regulated flows, such as a reservoir outflow station (particularly when intake levels are varied seasonally). Flow-independent, seasonal variance components are more likely to be detected in analysis of dissolved or inorganic nutrient concentrations (particularly nitrate) than in analysis of particulate or total nutrient concentrations.

In defining strata, one objective is to isolate homogeneous subgroups, based upon the flow/concentration relationship assumed by the calculation method (constant loading for Method 1, constant concentration for Methods 2 and 3, and log-linear flow/concentration relationship for Methods 4-6). A second objective is to set stratum boundaries so that the sampled and total flow distributions are equivalent within each stratum. This protects against bias in the loading estimates and applies particularly to high-flow strata. As described above, the method used to estimate error variance does not detect bias. If the flow distributions are not equivalent within each stratum, then minimum variance is less reliable as a criterion for selecting the "best" calculation method and loading estimate. Statistical and graphical tests are provided to compare flow distributions within each stratum.

Robustness of the loading estimate decreases as the number of statistical parameters which must be estimated from the sample data set increases. The number of parameters which must be estimated depends upon the calculation method and upon the number of strata. Methods 1 and 2 require one parameter estimate for each stratum. Methods 3, 4, 5, and 6 require two parameter estimates per stratum. Stratifying the data into two or three groups based upon flow and using Method 2 is generally adequate to capture the flow/concentration relationship while requiring the fewest parameter estimates (in statistical terms, using up the fewest degrees of freedom). If concentration does not vary systematically with flow, the need for flow stratification decreases.

Uncertainty in the loading estimate is reflected by the CV estimate reported for each calculation method. The CV equals the standard error of the mean loading divided by the mean loading. The CV reflects sampling error in the flow-weighted mean concentration. Potential error variance in the flow measurements are not considered in these calculations. In practice, CV values <0.1 are usually adequate for use in mass-balance modeling, especially considering that uncertainty in flow measurements is usually in this range. Depending on stream dynamics, CV values <0.1 may be very difficult to achieve, especially in small, flashy streams with strong C/Q relationships. CV values between 0.1 and 0.2 may be adequate for modeling purposes, especially for minor tributaries. If higher CVs are found, the user should consider refining and extending the stream monitoring program to obtain better data sets for load estimation before proceeding with modeling efforts. This particularly applies if the CV values are high for major tributaries.

For each calculation method, FLUX generates an inventory of sample and flow data in addition to a breakdown of the flow, load, and variance components within each stratum, as well as for the total strata, as demonstrated in Table 2.3, for the Caddo River example. Samples have been divided into three flow intervals. Complete output for this example is given at the end of this chapter.

Typically, most of the load and error variance is in the high-flow stratum. Since the variance component is roughly inversely related to sampling frequency within each stratum, the "breakdown by stratum" given in Table 2.3 is useful for evaluating sampling strategies. The low-flow stratum accounts for 55.4 percent of the total samples but only 4.6 percent of the total mass discharge. In future sampling, moving some of the samples from the low-flow to the high-flow stratum would reduce the variance of the total loading estimate. Alternatively, to reduce monitoring costs, the low-flow sampling frequencies could be reduced without substantially increasing the variance of the total loading estimate. FLUX also provides an estimate of the "optimal" sample distribution (expressed as percent of the total sampling effort allocated to each stratum, NEOPT% in Table 2.3) which would minimize the variance of the total loading estimate for a given total number of independent samples, using the equations specified in Table 2.2. Comparing the observed variance with the optimal variance provides an approximate indication of the potential benefits of optimizing the sample design. In this case, shifting from the historical sample distribution across flow strata (55%/36%/8%) to the optimal sample distribution (4%/21%/76%) would decrease the CV of the load estimate from 0.118 to 0.045.

As described by Bodo and Unny (1983, 1984), stratum breakdowns can be used to refine monitoring program designs for future years, subject to practical limitations in sample scheduling and total budget and to requirements imposed by other monitoring objectives. The "optimal" distribution of sampling effort indicated by the program may be difficult to achieve without automated equipment. An important statistical limitation is that the "optimal" allocation assumes that the samples are serially independent, and it may be impossible to take the recommended number of independent samples from intensively monitored strata. Five samples taken from different storm events would tend to be less serially dependent than five samples taken within one event, for example.

Because of these limitations, the "optimal" design should not be viewed as an absolute objective, but as a general direction for adjusting previous survey designs within practical constraints.

Diagnostics

FLUX includes several routines for generating scatter plots and histograms of flow, concentration, loading, and sample dates, as illustrated at the end of this chapter. The relationship between flow and concentration partially

Table 2.3
Breakdown by Flow Stratum - Caddo River Example

FLUX Breakdown by Stratum:

ST	NS	NE	FREQ DAYS	FLOW HM3/YR	FLUX KG/YR	VOLUME HM3	MASS KG	CONC PPB	CV -
1	93	93	582.0	120.23	2761.4	191.58	4400.1	23.0	.050
2	61	61	407.0	397.42	14501.1	442.85	16158.7	36.5	.092
3	14	14	107.0	2070.70	259357.2	606.61	75978.7	125.3	.148
***	168	168	1096.0	413.59	32171.8	1241.05	96537.5	77.8	.118

Optimal Sample Allocation:

ST	NS	NE	NE%	NEOPT%	FREQ%	VOL%	MASS%	VAR%	VARIANCE	CV
1	93	93	55.4	3.8	53.1	15.4	4.6	.0	.5276E+04	.050
2	61	61	36.3	20.8	37.1	35.7	16.7	1.7	.2442E+06	.092
3	14	14	8.3	75.5	9.8	48.9	78.7	98.3	.1407E+08	.148
***	168	168	100.0	100.0	100.0	100.0	100.0	100.0	.1432E+08	.118

Notes:

Output from the 'List/Breakdown' Procedure for Caddo River with 3 Flow Strata

The top part of the screen lists the distribution of samples, flows, fluxes, volume, and mass across strata for the current calculation method.

The middle part of the screen lists the distribution of sampling effort, flow days, flow volume, mass, and error variance, each expressed as percentage of the total.

The bottom part of the screen describes the potential benefit of optimizing the sample allocation across strata to obtain the lowest error variance for a fixed number of sampling events.

NE% = percent of total sample events in stratum
NEOPT% = optimal percent of total sample events in stratum

The reduction in error CV attributed to shifting from the current sample distribution (NE%) to the optimal distribution (NEOPT%) is listed. This can be used to refine future monitoring program designs. Generally, a shift towards more intense sampling of high-flow strata will be indicated.

determines the appropriate calculation method and should be reviewed in each application. Flow frequency distributions (sampled versus total) can also be graphically compared. These displays characterize the flow and concentration distributions and can assist the user in assessing data adequacy, identifying appropriate stratification schemes, and evaluating calculation methods.

The calculation methods differ with respect to the schemes used to estimate the loadings on the unsampled days or periods. For a given method, observed and predicted fluxes can be compared for each water quality sample. This provides one measure of performance. Ideally, the flux residuals (log10 (observed flux) minus log10(predicted flux) should be random and independent of flow season. In practice, this independence is sometimes difficult to achieve with the relatively simplistic models upon which the calculation methods are based. The residuals analysis procedure generates plots of observed versus predicted loadings, residuals versus flow, and residuals versus date. Alternative stratification schemes can be investigated to reduce the flow-dependence and/or time-dependence of the residuals.

Listings of residuals and jackknifed loading estimates are useful for identifying outliers and determining sensitivity of the loading estimates to individual samples. FLUX includes an outlier detection routine which can be used to delete suspected outliers from the sample data set. Outliers are detected based upon deviations of the residuals from a lognormal distribution (Snedecor and Cochran 1989). This procedure should be used conservatively. Detection of outliers depends upon the current stratification scheme and calculation method. Important information may be lost if an apparent outlier is actually an important signal. Suspected outliers are usually apparent on the concentration versus flow scatter plots. Developing confidence with the program, stratification scheme, and calculation method are suggested before using the outlier deletion procedure.

Program Operation

Introduction

This section describes the FLUX menu structure and operation procedures. When the program is run (from the DOS prompt), a series of help screens summarizing model features is first encountered. If error messages appear, it generally means that one of the FLUX program files has been corrupted or that your computer does not have enough available memory. Try reinstalling the program. Try unloading any memory-resident software. If you are trying to run the program from Windows, try exiting Windows and running directly from DOS. The introductory screens are followed by a menu which provides interactive access to eight types of procedures with the following functions:

```
                    F L U X  -  VERSION 4.5
Data   Calculate   Method   Plot   List   Utilities   Help   Quit

Data                Read and/or Stratify Data
Calculate      Calculate Loads Using Current Data & Stratification Scheme
Method         Select Flux Calculation Method Used in Plots & Tables
Plot                Plot Load, Flow, and/or Concentration Data
List                List Output Formats for Current Calculation Method
Utilities      Program Utilities & Options
Help                View Help Screens
Quit                End Session
```

A procedure category is selected by moving the cursor (using arrow keys) or by pressing the first letter of the procedure name. Selected procedures in the menu box are highlighted on the screen and underlined in the following documentation. Assistance in navigating around the menu can be obtained by pressing the <F7> function key. A Help screen describing the selected procedure can be viewed by pressing <F1>. After each procedure is completed, control returns to the above menu screen. Essential features of the current data set are summarized below the menu box (not shown here).

Data procedures

Data procedures control input, stratification, listing, and other manipulations of sample and/or flow data used in load calculations:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read   Stratify   Delete    Composite    FlowSub   Title    List

Read                 Read New Sample and/or Flow Data
Stratify  Divide Samples & Flows into Groups for Load Calculations
Delete          Delete a Specific Sample or Delete Excluded Samples
Composite       Composite Samples by Date
FlowSub         Substitute Daily Mean Flows for Sample Flows
Title           Enter New Title for Labeling Output
List                 List Sample or Flow Input Data
```

Four methods for reading in new sample or flow data are available under **Data/Read**:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read   Stratify   Delete    Composite    FlowSub   Title    List
Reset       Keep       Samples       Index

Reset           Read New Sample & Flow Data; Reset Stratification Scheme
Keep            Read New Sample & Flow Data; Keep Current Stratification Sch
Samples         Read New Sample Data Only; Keep Current Stratification Schem
Index           Read Sample & Flow Data from Station Index File
```

In the first three procedures, a data-entry screen is presented for defining all input specifications (data file names, variable labels, time periods, and units conversion factors). Use **Reset** to read in new flow data and reset the stratification scheme. Use **Keep** to read in new data without changing the current stratification scheme. Use **Samples** to read in new sample data only, without changing the current daily flow data or stratification scheme. Use **Index** to read in new data from a station index file, which is a user-created ASCII file defining the storage locations and formats for concentration and flow data referring to specific stations. Using index files greatly speeds and simplifies the specification of input data. (See Data-entry screens.)

If variable labels (for daily flows, sample flows, and concentration) are left blank on data entry screens, the user is prompted to select the appropriate field from a list of all fields contained in the source data file. Screen messages track the progress of data retrieval from disk files. If the specified data set has fewer than three samples or no daily flows, an error message appears and control returns to the main menu. Note that this may occur if the file names or variable labels are entered incorrectly. If a valid data set is retrieved, subsequent screens include a listing of missing or out-of-sequence daily flows (**Data/List/Missing** procedure) and a summary of the current stratification scheme (**Data/Stratify/List** procedure). Control then returns to the main menu.

Data/Stratify procedures divide the sample and flow data into groups based upon flow, date, and/or season. In many cases, stratification increases

the accuracy and precision of load estimates. At least three samples are required in each stratum. Four options are available:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read    Stratify   Delete    Composite    FlowSub   Title    List
Flow       General        Reset        List

Flow          Define Strata Based Upon Flow; Reset Data & Season Limits
General       Define General Stratification Scheme vs. Flow, Date, Season
Reset         Reset Stratification Scheme - Use 1 Stratum Only
List          List Current Stratification Scheme & Sample Counts
```

Stratifying based upon flow is often appropriate, especially when concentration is correlated with flow:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read    Stratify   Delete    Composite    FlowSub   Title    List
Flow       General        Reset        List
2 Strata       3 Strata       4 Strata       Other

2 Strata  Use 2 Flow Strata - Boundary at QMEAN
3 Strata  Use 3 Flow Strata - Boundaries at QMEAN/2, QMEAN x 2
4 Strata  Use 4 Flow Strata - Boundaries at QMEAN/2, QMEAN x 2, QMEAN x 8
Other     Use Flows to Define Strata; Enter Flow Bounds Directly
```

The first three procedures define flow boundaries automatically. Dividing the data into two strata based upon flow (low-flow and high-flow) is often appropriate. Three or more flow strata may be appropriate for relatively intensive data sets with strong flow/concentration relationships. The last procedure permits direct entry of flow boundaries. Each stratum must contain at least three sample events. If a stratum contains fewer then three events, the user is asked to redefine the flow boundaries until a valid stratification scheme is defined or the stratification scheme is reset.

Data/Delete procedures operate only on data stored in memory; they do not change disk files:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read    Stratify   Delete    Composite    FlowSub   Title    List
One        Excluded

One           Delete a Specific Sample
Excluded  Delete All Samples Excluded from Current Stratification Sche
```

The **Data/Composite** procedure combines samples collected on the same date or in the date interval into a single composite sample:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read    Stratify   Delete    Composite    FlowSub   Title    List

Composite       Composite Samples by Date
```

The user is prompted for the time interval (number of days) to be used for compositing samples. This optional procedure may be appropriate for data derived from intensive monitoring programs providing multiple samples per date. The composite sample concentration is the flow-weighted mean of the

individual samples. The composite sample flow is the average of the sample flows. Because of possible variations in actual event duration, it is generally preferable to composite samples prior to running FLUX; i.e., to specify event mean flows and event flow-weighted mean concentrations in the source data files.

The **Data/FlowSub** procedure can be used to test the sensitivity of load estimates to the types of flow measurements which are paired with sample concentrations:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read   Stratify   Delete    Composite    FlowSub   Title    List

FlowSub          Substitute Daily Mean Flows for Sample Flows
```

Depending upon source data files, input sample flows may be instantaneous flows measured at the time of sampling. The **Data/FlowSub** procedure replaces sample flows with daily mean flows on the corresponding sample dates. Samples are deleted if the corresponding daily mean flow is missing or zero. This flow substitution may also be performed in the **Data/Read** procedures by entering "Lookup" in the sample flow field.

Data/List procedures summarize the sample and/or flow data which have been retrieved from disk files:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read   Stratify   Delete    Composite    FlowSub   Title    List
Samples       Flows       Missing

Samples          List Sample Data
Flows            List Flow Data
Missing          List Missing or Out-of-Sequence Daily Flows
```

Before proceeding with load calculations, data listings should be reviewed to make sure that the correct sample and flow data have been retrieved from disk files. Both sample flows and corresponding daily mean flows are listed by the first two procedures. Daily flow data files read by FLUX are assumed to be sorted by date. The **Data/List/Missing** procedure lists missing or out-of sequence daily flow records. If any are detected, FLUX can still operate. It is desirable, however, to estimate any missing flows independently and to sort flow files before running FLUX.

Calculate procedures

Calculate procedures can be accessed after valid sample and flow data sets have been read and a valid stratification scheme has been defined. Three options are available:

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Compare   Loads    Series

Compare        Compare Sample Flow & Total Flow Distributions
Loads          Calculate Loads Using Each Method
Series         Generate Load Time Series
```

The **Calculate/Compare** procedure provides information which can be used to assess adequacy of the sample data and/or stratification scheme. The **Calculate/Loads** procedure lists average flows, flux rates, flow-weighted mean concentrations, and error estimates using each calculation method; this provides the basic information needed for BATHTUB applications.

The **Calculate/Series** procedure lists flow, load, and concentration time series using the currently selected calculation method. Four options are available:

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Compare    Loads    Series
Yearly      WtrYearly      Monthly      Daily

Yearly         Generate Load Time Series by Calendar Year
WtrYearly      Generate Load Time Series by Water Year
Monthly        Generate Monthly Load Time Series
Daily          Generate Daily Load Time Series
```

Time-series output does not include error estimates. These procedures are included primarily for generating load time series for use in applications other than BATHTUB which may require daily or monthly estimates.

Method procedure

The **Method** procedure asks the user to select the loading calculation method to be used in generating subsequent plots and output tables. Six choices are provided:

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
1 AVG LOAD    2 Q WTD C    3 IJC    4 REG 1    5 REG 2    6 REG 3

1 AVG LOAD     Method 1 - Mean Load
2 Q WTD C      Method 2 - Flow-Wtd-Mean Conc.
3 IJC          Method 3 - Flow-Wtd-Mean Conc. (IJC Modification)
4 REG 1        Method 4 - Regression Model 1
5 REG 2        Method 5 - Regression Model 2
6 REG 3        Method 6 - Regression Model 3 - log(C) vs. log(Q) Separate
```

Method 2 is initially selected as the default calculation method when the program is started. Descriptions of each method are given above (see Loading calculation methods); summary descriptions can be viewed by selecting a method and pressing the Help key <F1> or by running the **Help** procedure.

Plot procedures

Plot procedures provide important diagnostic information which can help in evaluating the adequacy of the current data set, stratification scheme, and calculation method:

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart    Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt

Barchart        Barcharts of Load, Mass, or Concentration Estimates
Conc            Plot Sample Concentrations  (ppb)
Load            Plot Sample Loads (kg/yr)
Flow            Plot Sample Flows (hm3/yr)
Daily           Plot Daily Flows (hm3/yr)
Qfreq           Plot Flow Frequency Distributions
Residuals       Plot Residuals = LOG10 ( Observed Load /Estimated Load )
GridOpt         Toggle Plot Grids On or Off
```

The **Plot/Barchart** procedures plot load, mass, flow-weighted mean concentration, or flow as a function of calculation method or stratum:

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart    Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
Load    Mass    Concs    Flow

Load            Load (kg/yr) Barcharts vs. Calculation Method or Stratum
   Method       Plot Load Estimates (kg/yr) vs. Calculation Method
   Stratum      Plot Load Estimates (kg/yr) vs. Stratum
Mass            Mass (kg) Barcharts vs. Calculation Method or Stratum
   Method       Plot Mass Estimates (kg) vs. Calculation Method
   Stratum      Plot Mass Estimates (kg) vs. Stratum
Concs           Flow-Weighted Concentration (ppb) vs. Calc. Method or Stratu
   Method       Flow-Weighted Concentration (ppb) vs. Calculation Method
   Stratum      Flow-Weighted Concentration (ppb) vs. Stratum
Flow            Mean Flow (hm3/yr) vs. Stratum
```

Each bar chart (except Flow) shows estimates $\pm$ 1 standard error. Plotting against method shows the sensitivity of the estimate (total across all strata) to the calculation method. Generally, a low sensitivity to calculation method would support the reliability of the load estimates. Plotting against stratum shows estimates for each data group using the currently selected calculation method.

Plot/Conc procedures display sample concentrations against four independent (x-axis) variables or a histogram:

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart    Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
Flow    Date    Month    Estimated    Histogram

Flow            Plot Sample Concentration (ppb) vs. Flow (hm3/yr)
Date            Plot Sample Concentration (ppb) vs. Date
Month           Plot Sample Concentration (ppb) vs. Month
Estimated       Plot Observed vs. Estimated Conc. for Current Calc. Method
Histogram       of Observed Concentrations (ppb)
```

Both the observed and the estimated sample concentrations are shown in the first three procedures. The "estimated" sample concentration is based upon

currently selected calculation method. Different symbols are used to indicate samples in different strata.

The **Plot/Load** and **Plot/Flow** procedures generate similar displays of sample data:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc    Load    Flow    Daily   Qfreq    Residuals   GridOpt
Flow    Date     Month   Estimated   Histogram

    Flow          Plot Load (kg/yr) vs. Flow (hm3/yr)
    Date          Plot Load (kg/yr) vs. Date
    Month         Plot Load (kg/yr) vs. Month
    Estimated     Plot Observed vs. Estimated Load
    Histogram     Histogram of Observed Loads (kg/yr)
```

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc    Load    Flow    Daily   Qfreq    Residuals   GridOpt
Date     Month    Histogram    Comparison    Both

    Date          Plot Sample Flows (hm3/yr) vs. Date
    Month         Plot Sample Flows (hm3/yr) vs. Month
    Histogram     Histogram of Sample Flows (hm3/yr)
    Comparison    Sample & Total Flow Histograms
    Both          Plot Sample Flow vs. Daily Mean Flow
```

Plot/Daily procedures display the entire flow record against date or month or as a histogram:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc    Load    Flow    Daily   Qfreq    Residuals   GridOpt
Date    Month    Histogram

    Date          Plot Daily Flows (hm3/yr) vs. Date
    Month         Plot Daily Flows (hm3/yr) vs. Month
    Histogram     Histogram of Daily Flows (hm3/yr)
```

Three format options are available for plotting daily flow against date:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc    Load    Flow    Daily   Qfreq    Residuals   GridOpt
Date    Month    Histogram
1Linear   2Log    3Filled

        1Linear    Plot Daily Flows (hm3/yr) vs. Date - Linear Scale
        2Log       Plot Daily Flows (hm3/yr) vs. Date - Log Scale
        3Filled    Plot Daily Flows (hm3/yr) vs. Date - Filled
```

In addition to plotting the daily flow values, each of these formats also indicates daily flows on the dates of sample collection (red squares). These displays are useful for identifying gaps in the sample record and for assessing sample coverage of major hydrograph features. The **1Linear** and **2Log** displays use different symbols to identify strata. The **3Filled** display does not identify strata. If zero flows are contained in the record, these are plotted as one-half of the lowest positive flow value in the **2Log** displays.

The **Plot/Qfreq** procedures display cumulative frequency distributions of sampled flow and total flow:

```
F L U X - VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
T Freq     V Freq

T Freq          Time Frequency Distributions for Sample & Total Flow
V Freq          Volume Frequency Distributions for Sample & Total Flow
```

In the first case, the y axis reflects the cumulative percentage of total samples or total flow days. In the second case, the y axis is the cumulative percentage of the total sample volume or total flow volume.

Plot/Residuals procedures display residuals for the current calculation method:

```
F L U X - VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
Conc     Load     Flow     Date     Month    Histogram    Autocor

Conc            Plot Residuals vs. Estimated Concentration (ppb)
Load            Plot Residuals vs. Estimated Load (kg/yr)
Flow            Plot Residuals vs. Sample Flow (hm3/yr)
Date            Plot Residuals vs. Sample Date
Month           Plot Residuals vs. Sample Month
Histogram       Histogram of Residuals for Current Calculation Method
Autocor         Plot Residual Autocorrelation - Resid(t) vs. Resid(t-1)
```

The residual is defined as log10(observed sample flux/estimated sample flux). Different symbols are used to identify strata. The **Autocor** procedure shows the lag-1 serial correlation of residuals with sample order based upon date. As discussed above (see Theory), serial correlation can influence the accuracy of error estimates and determine the appropriateness of time-series methods for estimating loads.

List procedures

List procedures can be accessed only if a valid data set and stratification scheme have been defined. Three tabular output formats are provided using the currently selected calculation method:

```
F L U X - VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Residuals       Breakdowns       Jackknife

Residuals       List Residuals & Screen for Outliers
Breakdowns      List Load & Flow Breakdowns by Stratum; Optimal Sample Alloc
Jackknife       List Jackknife Table for Current Calculation Method
```

List/Residuals procedures provide detailed listing of observed and predicted concentrations for the currently selected calculation method:

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Residuals        Breakdowns        Jackknife
All      Outliers    Signif

All          List All Residuals Without Screening for Outliers
Outliers     List Outliers
Signif       Set Significance Level for Outlier Screening
```

The first procedure lists observed concentrations, estimated concentrations, and residuals (log10 (observed/estimated)) for each sample. The second procedure has a similar format, but lists only samples which are suspected outliers. Outliers are detected based upon deviation from a lognormal distribution; see the associated help screen for a description of the outlier detection method. If any outliers are detected, the user may elect to delete them from the current sample list; source data files are not modified. The outlier detection procedure is iterative and automatically repeats itself until no outliers are detected. The last procedure sets the significance level for outlier screening (default = 0.05).

The **List/Breakdowns** procedure provides detailed information on the distribution of flow, flux, and error variance as a function of stratum for the current calculation method:

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Residuals        Breakdowns        Jackknife

Breakdowns       List Load & Flow Breakdowns by Stratum; Optimal Sample Alloc
```

The top half of this output screen shows the sample properties. The bottom half estimates the optimal sample allocation across strata based upon the current sample properties. The optimal allocation is defined as the distribution of sampling effort (percentage of total sample events in each stratum) which leads to the lowest error in the load estimate. This information can be used to refine future data-collection efforts.

The **List/Jackknife** procedure shows the derivation of the error variance estimate for the current calculation method:

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Residuals        Breakdowns        Jackknife

Jackknife        List Jackknife Table for Current Calculation Method
```

Each sample event is excluded, one at a time, from the sample set and the load estimate is recalculated using data from the remaining sample events. The procedure lists and displays the distribution of load estimates with each sample event excluded. This can be used to identify samples which have a relatively large impact on the computed average loads.

Utilities procedures

Utilities procedures allow the user to redirect program output, view disk files, or modify the default settings for various program options:

```
F L U X  -  VERSION 4.5
Data     Calculate    Method    Plot    List    Utilities    Help    Quit
Output       View       Set

Output    Select Output Destination for Text
View      View any DOS File
Set       Set Miscellaneous Program Options & Parameters
```

The **Utilities/Output** procedure redirects program output to a disk file or to screen:

```
F L U X  -  VERSION 4.5
Data     Calculate    Method    Plot    List    Utilities    Help    Quit
Output       View       Set
Screen    File

Screen    Send Output to Screen (Default)
File      Send Output to Disk File
```

The selected output destination remains in effect until it is reset. Even if **Screen** is selected, individual output screens can be copied to disk files after viewing.

The **Utilities/View** procedure views any DOS file stored in ASCII format:

```
F L U X  -  VERSION 4.5
Data     Calculate    Method    Plot    List    Utilities    Help    Quit
Output       View       Set

View      View any DOS File
```

Only the first 80 columns of each record are displayed.

Utilities/Set procedures modify the default settings for various program options:

```
F L U X  -  VERSION 4.5
Data     Calculate    Method    Plot    List    Utilities    Help    Quit
Output       View       Set
Events     Signif    Restrict   Method 6

Events    Define Maximum Event Duration (Days) For Grouping Samples
Signif    Set Significance Level for Testing Flow/Conc Regression
Restrict  Toggle Option to Restrict Flow Ranges for Model Application
Method 6  Toggle Option for Error Analysis Using Calc Method 6
```

The **Utilities/Set/Events** procedure sets the maximum duration of an independent sampling event for the purpose of estimating error variances:

```
F L U X  -  VERSION 4.4
Data     Calculate    Method    Plot    List    Utilities    Help    Quit
Output       View       Set
Events     Signif    Restrict   Method 6

Events    Define Maximum Event Duration (Days) For Grouping Samples
```

This setting does not influence mean load estimates. The default setting is 1 day. If the sample record contains hydrographic events lasting longer than 1 day and if multiple samples are collected within events, settings longer than 1 day may be appropriate.

The **Utilities/Set/Signif** sets the statistical significance level required before flow/concentration regression models are applied in calculating loads:

```
                    F L U X  -  VERSION 4.5
Data     Calculate    Method    Plot    List    Utilities    Help    Quit
Output       View       Set
Events     Signif   Restrict   Method 6

Signif    Set Significance Level for Testing Flow/Conc Regression
```

This setting only influences loads calculated using Method 4, Method 5, or Method 6. The **Signif** setting has a valid range of 0.0 to 1.0. If **Signif** = 0.0, the sample regressions are never used; the slope of the log concentration versus log flow relationship is always set to 0.0 before calculating loads. If **Signif** = 1.0 (default), the regression slope calculated from the sample record is always used (regardless of its significance level). If **Signif** = 0.05, the sample regression slope is used only if it is different from zero at the 0.05 significance level.

The **Utilities/Set/Restrict** toggles the option to restrict concentration versus flow regressions to the range of sampled flows:

```
                    F L U X  -  VERSION 4.5
Data     Calculate    Method    Plot    List    Utilities    Help    Quit
Output       View       Set
Events     Signif   Restrict   Method 6

Restrict  Toggle Option to Restrict Flow Ranges for Model Application
```

This setting only influences loads calculated using Method 6. If the **Restrict** setting is on (default), daily flows are restricted to the range of sample flows before applying the regression to calculate loads. For example, if the maximum sampled flow is 98 hm^3/year, the predicted concentration at a flow of 98 hm^3/year is applied to all days when the flow exceeds 98 hm^3/year. If the **Restrict** setting is off, extrapolation of the regression beyond the range of sampled flows is permitted; this is risky, but may be appropriate if the slope is well defined from the sample data and if the extrapolation is not over a wide flow range. This option will have no effect if the range of sample flows equals or exceeds the range of daily flows, which is the desired situation when data are derived from an ideal sampling program. The setting turns on and off each time the **Restrict** procedure is selected. A screen message beneath the menu indicates the current setting.

The **Utilities/Set/Method 6** procedure toggles the option to conduct error analysis calculations using Method 6:

```
                    F L U X  -  VERSION 4.5
Data     Calculate    Method    Plot    List    Utilities    Help    Quit
Output       View       Set
Events     Signif    Restrict   Method 6
```

Method 6 Toggle Option for Error Analysis Using Calc Method 6

If **Method 6** setting is on (default), error estimates are calculated for Method 6. Depending upon the numbers of sample and daily flow records, these calculations can be time-consuming because the concentration/flow regression is applied separately to each daily flow. If the **Method 6** setting is off, error analyses are not conducted and the CV of the Method 6 load estimate is set to 0.0. The setting turns on and off each time the procedure is selected.

Help procedure

Supplementary help screens can be viewed from the program menu by selecting the **Help** procedure:

```
                    F L U X  -  VERSION 4.5
Data     Calculate    Method    Plot    List    Utilities    Help    Quit

Help                  View Help Screens
Quit                  End Session
```

This provides access to help screens that are organized in seven categories, as summarized below:

```
  HELP TOPICS
> INTRODUCTORY SCREENS
  PROGRAM MECHANICS
  GLOSSARY
  DATA FILE FORMATS
  CALCULATION METHODS
  OUTPUT FORMATS
  GENERAL GUIDANCE
```

A help category is selected by moving the cursor and pressing <Enter>. A list of the help screens available in the selected category is presented. Context-sensitive help screens can also be accessed during execution of other procedures by pressing the <F1> function key. The general **Help** menu can also be accessed from any Data-Entry screen by pressing <F9>.

Quit procedure

```
                    F L U X  -  VERSION 4.5
Data     Calculate    Method    Plot    List    Utilities    Help    Quit

Quit                  End Session
```

Selecting **Quit** from the main menu ends the current session after user verification.

Typical Application Sequence

Flux input data files can be generated using formats described below (see Data File Formats). The user directs the flow of the program through the four-level tree menu screen described in the previous section. A Documented Session showing steps involved in a typical application is provided at the end of this chapter. The program starts by reading in the concentration and flow data and using the data files and date ranges specified by the user. Data stratification can be defined/redefined at any time, based upon flow, date, and/or season ranges. The analysis is subsequently directed from the main menu, which includes categories of procedures. After executing a given procedure, the program returns to the main menu for another selection.

Because each loading estimation problem is unique, it is impossible to specify a "universal" pathway for the analysis. In some cases, a few iterations (mainly involving alternative strata definitions) would be required before arriving at an acceptable loading estimate. Generally, however, a typical program application sequence is outlined in Table 2.4.

Further steps would involve, but not be limited to, refinement of the stratification scheme, testing of alternative models, deletion of outliers, and testing for trends.

The selection of the "best" loading estimate to be used in subsequent modeling efforts is up to the user, based upon the following criteria:

a. Calculation method and stratification scheme yielding minimum estimated variance in the mean loading estimate.

b. Sensitivity of the loading estimate to alternative calculation methods, stratification schemes, and individual samples.

c. Residuals analysis results.

The selection can be based primarily upon minimum estimated variance, provided that the following conditions are met (corresponding FLUX procedures are listed in parentheses):

a. Sampling is representative; date and flow ranges are reasonably well covered. **(Plot/Daily/Date, Calculate/Compare)**.

b. Sampled and total flow means are equal within each stratum **(Calculate/Compare, Calculate/Loads)**.

c. Residuals are reasonably independent of date, season, and flow. **(Plot/Residuals/Date,Month,Flow)**.

d. Residuals are serially independent. **(Plot/Residuals/Autocorr)**.

Table 2.4
Typical Application Sequence

Step	Menu Selections	Function
1	Data/Read/Reset or Data/Read/Index	Read sample and flow data from disk
2	Plot/Daily/Date	Plot daily flow record, showing sample dates
3	Calculate/Compare	Compare sample and total flow distributions
4	Data/Stratify/Flow/2Strata	Stratify into two groups at mean flow
5	Plot/Conc/Flow	Plot concentration versus flow
6	Calculate/Loads	Calculate loads using each method
7	Plot/Barchart/Loads/Method	Plot loads versus calculation method
8	Method	Select calculation method start with Method 2
9	Plot/Loads/Estimated	Observed versus estimated loads on sample dates
10	Plot/Residuals/Date	Test for time dependence of residuals
11	Plot/Residuals/Month	Test for seasonal dependence of residuals
12	Plot/Residuals/Flow	Test for flow dependence of residuals
13	[Reiterate]	Review results Return to Step 4 or 8 Increase flow strata until methods converge Try other calculation methods Try using daily flows in place of inst. flows
14	List/Breakdowns	List breakdown by stratum optimal sample allocation

e. Sampling events are independent; for intensive data sets only. **(Utilities/Set/Events).**

If the above conditions are marginally satisfied or cannot be met because of existing data limitations, factors other than minimum variance (sensitivity and residuals analyses) should be given greater weight. Further sampling may be indicated, particularly if the tributary accounts for a major portion of the total reservoir loading.

Differences among the various calculation methods should be interpreted in relation to the estimated variances. For example, a range of 45 to 50 kg/year in the mean loading estimate is of little significance if the estimated coefficients of variation are on the order of 0.1 or greater. Provided that flow regimes are adequately sampled, limited variation among calculation methods suggests robust results. Calculation Methods 2 or 3 are generally the most robust and should be used (typically with flow stratification into two groups with the boundary set near the mean flow) if load estimates must be generated from limited data not conforming rigidly to the above criteria.

A general approach is to refine the stratification scheme so that estimates for six calculation methods converge to a common result. This occurs when the mean estimates for Methods 1-6 are not significantly different from each other. The uncertainty of the estimates (CVs) may differ substantially, however. In most cases, the Method 2 estimate will have the lowest uncertainty and should be used if convergence is reached. A regression estimate (usually Method 6) may have the lowest uncertainty if stratification alone does not capture essential features of the flow/concentration relationship, especially if flow and concentration are strongly correlated within the highest flow stratum.

In applications to small, flashy streams or storm sewers, special consideration must be given to the specification of sample flows. In flashy streams, the variance and extremes of instantaneous sample flows will be considerably higher than the variance and extremes of daily mean flows. This can cause severe bias in the load estimates when (a) concentration varies with flow, and (b) either the data are stratified based upon flow or a regression method (4-6) is used. To avoid this bias, the time scale (averaging period) of the sample flows should be equivalent to the time scale of the daily flows. This can be accomplished in one of two ways:

a. Preprocess the instantaneous flows and sample concentrations so that each sample record read by FLUX represents a daily mean flow and daily flow-weighted mean concentration.

b. Read the instantaneous flows and sample concentrations into FLUX. Run the "Data/Composite" procedure to calculate a daily flow-weighted mean concentration for each sample day. Then run the "Data/FlowSub" procedure to substitute daily mean flows for sample mean flows. Then proceed with load calculations.

This type of problem is generally indicated when the mean sample flow in the highest flow stratum is significantly higher than the mean daily flow (Calculate/Compare or Calculate/Loads procedures). It is also revealed by plotting sample flows against daily mean flows (Plot/Flow/Both procedure). If the sample flow rates generally exceed the daily flow rates (particularly in the high-flow range), one of the preprocessing steps outlined above should be taken. In any application where instantaneous samples are used, it is generally a good idea to test whether substitution of daily mean flows has an effect

on the load estimates. If such an effect is indicated, estimates based upon daily mean flows are less likely to be biased.

In a reservoir eutrophication study, FLUX can be used to estimate annual (October-September) and seasonal (May-September) loadings of total phosphorus, ortho-phosphorus, total nitrogen, inorganic nitrogen, and a conservative substance for each sampled tributary and outflow. For annual calculations, water-year loadings (October-September) are generally more appropriate than calendar-year loadings for use in predicting growing-season water quality in the reservoir pool. Unless flow/concentration/seasonal dynamics differ markedly among the nutrient components, it is a good idea to use the same stratification scheme for each component. The stratification scheme can be optimized for calculating total phosphorus loading (usually the most important) and subsequently used in calculating other component loadings.

Procedure Outline

Following is a list of all FLUX procedures. Names are listed on the left. Indentation reflects Menu level (Lines 1-4). A brief description of each procedure is given on the right.

```
Data                Read and/or Stratify Data
   Read             Read New Sample and/or Flow Data
      Reset         Read New Sample & Flow Data; Reset Stratification Scheme
      Keep          Read New Sample & Flow Data; Keep Current Stratification Sch
      Samples       Read New Sample Data Only; Keep Current Stratification Schem
      Index         Read Sample & Flow Data from Station Index File
   Stratify         Divide Samples & Flows into Groups for Load Calculations
      Flow          Define Strata Based Upon Flow; Reset Data & Season Limits
         2 Strata   2 Flow Strata - Boundary at QMEAN
         3 Strata   3 Flow Strata - Boundaries at QMEAN/2, QMEAN x 2
         4 Strata   4 Flow Strata - Boundaries at QMEAN/2, QMEAN x 2, QMEAN x 8
         Other      Use Flows to Define Strata; Enter Flow Bounds Directly
      General       Define General Stratification Scheme vs. Flow, Date, Season
      Reset         Reset Stratification Scheme - Use 1 Stratum Only
      List          List Current Stratification Scheme & Sample Counts
   Delete           Delete a Specific Sample or Delete Excluded Samples
      One           Delete a Specific Sample
      Excluded      Delete All Samples Excluded from Current Stratification Sche
   Composite        Composite Samples by Date
   FlowSub          Substitute Daily Mean Flows for Sample Flows
   Title            Enter New Title for Labeling Output
   List             List Sample or Flow Input Data
      Samples       List Sample Data
      Flows         List Flow Data
      Missing       List Missing or Out-of-Sequence Daily Flows

Calculate           Calculate Loads Using Current Data & Stratification Scheme
   Compare          Compare Sample Flow & Total Flow Distributions
   Loads            Calculate Loads Using Each Method
   Series           Generate Load Time Series Using Current Model
      Yearly        Generate Load Time Series by Calendar Year
      WtrYearly     Generate Load Time Series by Water Year
      Monthly       Generate Monthly Load Time Series
      Daily         Generate Daily Load Time Series
Method              Select Flux Calculation Method Used in Plots & Tables
   1 AVG LOAD       Method 1 - Mean Load
   2 Q WTD C        Method 2 - Flow-Wtd-Mean Conc.
   3 IJC            Method 3 - Flow-Wtd-Mean Conc. (IJC Modification)
   4 REG 1          Method 4 - Regression Model 1
```

5 REG 2	Method 5 - Regression Model 2
6 REG 3	Method 6 - Regression Model 3 - log(C) vs. log(Q) Separate
Plot	Plot Load, Flow, and/or Concentration Data
Barchart	Barcharts of Load, Mass, or Concentration Estimates
Load	Load (kg/yr) Barcharts vs. Calculation Method or Stratum
Method	Plot Load Estimates (kg/yr) vs. Calculation Method
Stratum	Plot Load Estimates (kg/yr) vs. Stratum
Mass	Mass (kg) Barcharts vs. Calculation Method or Stratum
Method	Plot Mass Estimates (kg) vs. Calculation Method
Stratum	Plot Mass Estimates (kg) vs. Stratum
Concs	Flow-Weighted Concentration (ppb) vs. Calc. Method or Stratu
Method	Flow-Weighted Concentration (ppb) vs. Calculation Method
Stratum	Flow-Weighted Concentration (ppb) vs. Stratum
Flow	Mean Flow (hm3/yr) vs. Stratum
Conc	Plot Sample Concentrations (ppb)
Flow	Plot Sample Concentration (ppb) vs. Flow (hm3/yr)
Date	Plot Sample Concentration (ppb) vs. Date
Month	Plot Sample Concentration (ppb) vs. Month
Estimated	Plot Observed vs. Estimated Conc. for Current Calc. Method
Histogram	Histogram of Observed Concentrations (ppb)
Load	Plot Sample Loads (kg/yr)
Flow	Plot Load (kg/yr) vs. Flow (hm3/yr)
Date	Plot Load (kg/yr) vs. Date
Month	Plot Load (kg/yr) vs. Month
Estimated	Plot Observed vs. Estimated Load
Histogram	Histogram of Observed Loads (kg/yr)
Flow	Plot Sample Flows (hm3/yr)
Date	Plot Sample Flows (hm3/yr) vs. Date
Month	Plot Sample Flows (hm3/yr) vs. Month
Histogram	Histogram of Sample Flows (hm3/yr)
Comparison	Sample & Total Flow Histograms
Both	Plot Sample Flow vs. Daily Mean Flow
Daily	Plot Daily Flows (hm3/yr)
Date	Plot Daily Flows (hm3/yr) vs. Date
1Linear	Plot Daily Flows (hm3/yr) vs. Date - Linear Scale
2Log	Plot Daily Flows (hm3/yr) vs. Date - Log Scale
3Filled	Plot Daily Flows (hm3/yr) vs. Date - Filled
Month	Plot Daily Flows (hm3/yr) vs. Month
Histogram	Histogram of Daily Flows (hm3/yr)
Qfreq	Plot Flow Frequency Distributions
T Freq	Time Frequency Distributions for Sample & Total Flow
V Freq	Volume Frequency Distributions for Sample & Total Flow
Residuals	Plot Residuals = LOG10 (Obs./Est.) Loads with Regression
Conc	Plot Residuals vs. Estimated Concentration (ppb)
Load	Plot Residuals vs. Estimated Load (kg/yr)
Flow	Plot Residuals vs. Sample Flow (hm3/yr)
Date	Plot Residuals vs. Sample Date
Month	Plot Residuals vs. Sample Month
Histogram	Histogram of Residuals for Current Calculation Method
Autocor	Plot Residual Autocorrelation - Resid(t) vs. Resid(t-1)
GridOpt	Toggle Plot Grids On or Off
List	List Output Formats for Current Calculation Method
Residuals	List Residuals & Screen for Outliers
All	List All Residuals Without Screening for Outliers
Outliers	List Outliers
Signif	Set Significance Level for Outlier Screening
Breakdowns	List Load & Flow Breakdowns by Stratum; Optimal Sample Alloc
Jackknife	List Jackknife Table for Current Calculation Method
Utilities	Program Utilities & Options
Output	Select Output Destination for Text
Screen	Send Output to Screen (Default)
File	Send Output to Disk File
View	View any DOS File
Set	Set Program Options & Parameters
Events	Define Maximum Event Duration (Days) For Grouping Samples

Signif	Set Significance Level for Testing Flow/Conc Regression
Restrict	Toggle Option to Restrict Flow Ranges for Model Application
Method 6	Toggle Option for Error Analysis Using Calc Method 6
Help	View Help Screens
Quit	End Session

Data-Entry Screens

Following is a listing of each data-entry screen in FLUX and its associated HELP file. These are accessed via the Data/Read or Data/Stratify procedures. The help screens are accessed by hitting <F1>. Additional help screens containing more detailed information on specific fields may be obtained by moving the cursor to the field and hitting <F8>; this works only when the message "<F8> =HELP FIELD" appears in the lower right corner of the screen.

DATA-ENTRY SCREEN: Data/Read/Reset, Keep, or Samples

```
                    FLUX INPUT SCREEN

TITLE:                 ______________________________
DOS PATH:              ______________________________

FLOW DATA FILE:        ______________________________
FLOW LABEL:            ________

SAMPLE DATA FILE:      ______________________________
SAMPLE STATION CODE:   ________
CONC VARIABLE:         ________  CONC UNIT FACTOR:  ________
FLOW VARIABLE:         ________  FLOW UNIT FACTOR:  ________
                                 FLOW SIGN (1 or -1)________

SCREENING VARIABLE:    ________  RANGE: ________ TO ________

SAMPLE DATE RANGE: >= ______  < ______  (YYMMDD)
FLOW DATE RANGE:   >= ______  < ______  (YYMMDD)
SEASON RANGE:      >= _____   < _____   (MMDD)
```

HELP SCREEN:

```
Data Read

Read input sample & flow data from disk files.

PATH specifies directory for input files (e.g., C:\FLUX)

Input file formats specified by file extensions:
    'file.FLX'  - original FLUX format
    'file.WK1'  - LOTUS-123 Worksheet
    'file.DAT'  - free-format ASCII File
    'file.ASC'  - alternative free-format ASCII
    'file.FLO'  - alternative free-format for daily flows
Use Procedure 'Help' or <F9> to get description of file formats.

CONCENTRATION & FLOW SCALE FACTORS are read from .FLX files. They
must be entered on screen for other input file formats.  Use a flow
scale factor of .8937 if file flows are in ft3/sec (cfs).

If CONC or FLOW labels are blank, user will be asked to select them
from list of all fields contained in file.

Press <F8> to get help on specific input fields.
```

DATA-ENTRY SCREEN: Data/Read/Index:

```
READ SAMPLE & FLOW DATA FROM STATION INDEX FILE

TITLE:                  ______________________________

DOS PATH:               ______________________________

STATION INDEX FILE:     ______________________________

SCREENING VARIABLE:  ________   RANGE: ________ TO ________

SAMPLE DATE RANGE: >= ______  < ______  (YYMMDD)

FLOW DATE RANGE:   >= ______  < ______  (YYMMDD)

SEASON RANGE:      >= _____   < _____   (MMDD)
```

HELP SCREEN:

```
Data Read Index

Reads New Samples & Flows from data files specified in a
Station Index File (*.IDX).  Station Index Files facilitate
access to sample and flow data.  Suggest creating a separate
index file for each project or reservoir.

An ASCII text editor (e.g. DOS EDIT) is required to create
or edit an index file (outside of FLUX).

Use one of the sample index files (*.IDX) as a template.

If the TITLE is blank, station label will be assigned.

If the index file name is blank, user will be prompted to select
from a list of all index files stored in the current PATH.

Resets stratification scheme after data are read.

See 'Help - Station Index File Format' for details.
```

DATA-ENTRY SCREEN: Data/Stratify/Flow

```
        STRATIFY BASED UPON FLOW
            UNITS =  HM3/YEAR

    MEAN FLOW:        ________
    MAXIMUM FLOW:     ________

                                  SAMPLE      FLOW
STRATUM  UPPER FLOW LIMIT          COUNT      COUNT

   1     <  __________            _____      _____

   2     <  __________            _____      _____

   3     <  __________            _____      _____

   4     <  __________            _____      _____

   5     <  __________            _____      _____
```

HELP SCREEN:

```
Data Stratify Flow

Divide sample & flow data into groups or strata based upon flow.

Set upper bound for flow in each stratum.

Sample included in stratum if flow < upper bound.

Season & date ranges are reset.

Flow bounds must be in increasing order.

To include all data, upper bound of last defined stratum
should exceed maximum flow.

Set upper flow limit to 0 for unused strata.
```

DATA-ENTRY SCREEN: Data/Stratify/General

```
                    DEFINE STRATIFICATION SCHEME

     FLOWS-(HM3/YR)   DATE-(YYMMDD) SEASON-(MMDD)   PREVIOUS
STR >=MIN    < MAX    >=MIN  < MAX  >=MIN  < MAX   SAMP  FLOWS

 1 _______-_______ ______-_____ ___ - ___  ___ _______
 2 _______-_______ ______-_____ ___ - ___  ___ _______
 3 _______-_______ ______-_____ ___ - ___  ___ _______
 4 _______-_______ ______-_____ ___ - ___  ___ _______
 5 _______-_______ ______-_____ ___ - ___  ___ _______
```

HELP SCREEN:

```
Data Stratify General

Divide sample & flow data into groups or strata based upon flow,
date, and/or season.

Sample & flow counts for previous stratification scheme (before
editing) are shown on right.

Set limits to 0,0 to include all data.

Also, if MIN=MAX, all data are included.

Seasonal Definitions Wrap Around Calendar, e.g.:
    MIN= 0401, MAX=1001  (samples between April 1 & Sept 30)
    MIN= 1001, MAX=0401  (samples between Oct 1 & March 31)

Samples and flows not within any defined stratum are excluded
from load calculations & displays.
```

Data File Formats

FLUX requires input data files containing sample data (i.e., the concentrations and instantaneous flows) and flow data (i.e., the continuous flow record for the period of interest). Experience with the program indicates that most of

the effort required to apply the program involves setting up the required data files. Several format options are provided to facilitate this task. Five data-file formats are supported for sample and flow data records. One format is supported for the optional station index file. Brief descriptions, naming conventions, and file names are given in Table 2.5.

Table 2.5
FLUX File Formats

File Format	Naming Convention	File Contents	Examples
FLUX formatted	*.FLX	Sample and flow data	CADDO.FLX
ASCII	*.DAT	Sample data Flow data	CADDO_S.DAT CADDO_Q.DAT
ASCII	*.ASC	Sample data	CADDO_S2.ASC
ASCII	*.FLO	Flow data	CADDO.FLO
Lotus-123 Release 2.X	*.WK1	Sample data " " Flow data	CADDO_S.WK1 CADDO_S1.WK1 CADDO_S2.WK1 CADDO_Q.WK1
ASCII	*.IDX	Station index	CADDO.IDX

Although only one spreadsheet format is provided (*.WK1), most other spreadsheet programs (including Windows versions) can export files in the .WK1 format. Lotus WK3 and WK4 (Windows) file formats are not equivalent to the WK1 format. If a Windows version of Lotus is being used, all of the data must be stored on the first page of the worksheet, and the .WK1 extension must be specified in saving the file. If the user's spreadsheet program cannot save or convert files to the .WK1 format, data can be printed to a disk as an ASCII file and edited to comply with one of the ASCII formats described below.

The following general rules apply to all file formats (except where noted):

a. A Date field must be included, labeled at the top of the file as follows:
DATE Lotus-123 date (Days from Jan 1, 1900), or
YYMMDD year-month-day format, numeric value
(This does not apply to the *.FLX format in which dates are always assumed to be in YYMMDD format). Dates cannot be specified as character strings.

b. Spreadsheet columns must be contiguous starting with Column A (no blank columns).

c. Spreadsheet Rows must be contiguous (reading stops at first blank row). Entries beyond the first blank row in a spreadsheet are ignored.

d. Sample files can be sorted in any order.

e. Daily flow files should be sorted by date.

f. Missing values are identified using the missing value codes specified at the top of the file (ASCII formats).

g. Blank fields in spreadsheets are assumed missing. If a blank field is intended, make sure that it is truly blank and not a character field filled with spaces; the latter will be interpreted as zero (not necessarily missing).

h. For concentrations, blank, negative, zero values, or character strings are assumed missing.

i. For daily flows, negative or zero values (other than the specified missing value code) or character strings are interpreted as zeroes (no flow).

j. With the exception of the optional station field in the first column of sample worksheets, all spreadsheet entries should be numeric values or blank. Character constants are interpreted as zeroes. Computed fields in spreadsheets (numeric values assigned by formulas) are acceptable for all fields except the optional station field (character string).

k. In specifying file names, variable labels, and station codes, case is not significant (i.e., "sta1" = "STA1" = "StA1").

l. A maximum of 64 fields (columns) can be contained in the sample or flow data sets. FLX format files can contain up to seven fields.

Each file format is described in detail below. Examples are provided on the program diskette.

*.FLX Format for Sample & Flow Data

This format is indicated by the .FLX file extension. This fixed-format file contains both sample data and daily flow data. The file contains four groups:

Group 1: **Title** (maximum = 48 characters)
FORMAT (6A8)

Group 2: Variable Index - ID, LABEL, CF
FORMAT (I2,1X,A8,F8.0)

ID = Integer subscript (maximum = 7)

LABEL = Flow and water quality variable label (e.g.,TOTALP, FLOW) (maximum = 8 characters)

CF = Factor to convert data units to program units
Program Units = MILLION M^3/YR (hm^3/yr) for flow
Program Units = MG/M^3 = PPB for concentration

NOTES:

a. Conversion factors contained in the input file will override those specified on the input screen.

b. If the flow lookup option is used (sample flows retrieved from daily flows), the appropriate flow conversion factor must be specified on the FLUX data-entry screen.

c. The order of variable labels must correspond to that specified in Data Group 3 (columns).

d. The last record of Data Group 2 must be - "00".

Group 3: Water Quality Records - DATE, S, (C(I),I=1,N)
FORMAT (F6.0,2x,7F8.0)

DATE = Date in YYMMDD format (e.g., 840126)

C(I) = Data value (include decimal points or right-justify in field; entries that are blank, zero, or negative are assumed to be missing). At least one of these should refer to sample concentration. The sample flow field is optional if the 'Lookup' option is specified when retrieving data.

N = Number of variable indexes defined in Group 2

NOTES:

a. The last record of Data Group 3 must be - "000000".

b. Include one record for each sample (maximum samples = 500).

c. Use blanks, zeros, or negative values for missing concentrations or sample flows.

Group 4: Flow Distribution Records - DATE, FLOW
FORMAT (F6.0,2x,F8.0)

DATE = Date in YYMMDD format

FLOW = Flow must be in the same units as the sample flows specified in Group 3. Include decimal point or right-justify in field. Zero or negative entries are valid. Blank values are interpreted as zeros (omit the entire record if flow is missing for a given date).

NOTES:

a. The last record of Data Group 4 must be - "000000".

b. Include one record for each mean daily flow (maximum flow records = 7000).

The file 'CADDO.FLX' is an example of this format:

```
degray inflow, Jan 78 - Dec 80 - flows in cms                    Group 1
id-label----cf-----                                              Group 2
01 flow      31.56
02 total p   1.
03 total dp  1.
04 ortho p   1.
00
dates       flow  total p    tdp   ortho p                      Group 3
780102      4.70   12.00    4.00    4.00
780109      4.39   11.00   10.00    4.00
780117     47.00   71.00    0.00    4.00
780123      9.08   18.00    0.00    8.00
780130     16.30   19.00    0.00    0.00
etc.
810922      2.98   16.00    9.00    8.00
810929     13.80   23.00   14.00   10.00
000000
date        flow                                                 Group 4
780101      5.09
780102      4.66
780103      4.66
780104      4.66
etc.
801229      4.35
801230      4.25
801231      4.13
000000
<EOF>
```

*.DAT ASCII Format for Sample or Flow Data

This format is specified by the '.DAT' file extension. This is a free-format ASCII file. Column locations are not significant. Entries are separated by spaces or commas. The layout is as follows:

Line 1	Title
Line 2	Number of Variables = M (columns in database)
Line 3	Missing Value Code (Typically zero or negative)
Line 4 to 3+M	Variable Labels (Max 8 Characters Per Label)
Line 3+M...n	Data Records (Any Number, Max 500 used at one time)

Variable labels must include a date field labeled as:

YYMMDD	for dates in YYMMDD Format, or
DATE	for dates in Lotus Format (# Days from Jan 1, 1900)

Variable labels may include sample flows, concentrations, screening variables, or other record identifiers. Columns must be contiguous (no blank columns). Rows (data records) must also be contiguous. Sample records can be sorted in any order.

Units conversion factors are not included in the file. These must be specified on the FLUX Input Screen or in the station index file (see below).

The file 'CADDO_S.DAT' is an example of this format for sample records:

```
degray inflow flows in cms
5
0
yymmdd
flow
tp
total dp
ortho p
780102   4.7    12     4     4
780109  4.39    11    10     4
etc.
810922  2.98    16     9     8
810929  13.8    23    14    10
<EOF>
```

The file 'CADDO_Q.DAT' is an example of this format for daily flow records:

```
degray inflow, Jan 78 - Dec 80 - flows in cms
2
-999
yymmdd
flow
780101      5.09
780102      4.66
780103      4.66
etc.
801230      4.25
801231      4.13
<EOF>
```

*.ASC ASCII Format for Sample Records

This alternative ASCII format for sample data can be used (instead of *.DAT format) for files containing data for more than one station. The file layout is as follows:

Line 1	'Title' (enclosed in single quotes)
Line 2	Number of Fields (columns) = Nfields
Line 3	Missing Value Code
Lines 4 thru 3+Nfields	'Field Labels' (enclosed in single quotes)
Lines 4+Nfields etc	Sample Records, free-format

Each sample record contains station code, date, and numeric fields.

All character entries in this file must be enclosed in 'single quotes'. This includes the title line, field labels, and station labels. Fields are delimited by spaces or commas.

The first data field (column) is used to specify 8-character station codes, enclosed in 'single quotes'.

The file 'CADDO_S2.ASC' is an example of this format for sample records:

```
'degray inflow, flows in m3/sec - dates in yymmdd format'
  6
-999.999
 'Station'
 'yymmdd'
 'flow'
 'tp'
 'tdp'
 'orthop'
'Caddo' 780102 4.7 12 4 4
'Caddo' 780109 4.39 11 10 4
'Caddo' 780117 47 71 -999.999 4
etc.
'Caddo' 810915 3.25 48 15 15
'Caddo' 810922 2.98 16 9 8
'Caddo' 810929 13.8 23 14 10
<EOF>
```

Although this example includes data from only one station, records from other stations can be included in the file; the program will select the appropriate records based upon the sample station code specified on the FLUX Input Screen. If the specified sample station code is blank, all records are selected.

*.FLO ASCII Format for Daily Flow Data

This ASCII format for daily flow records is indicated by the '.FLO' extension. This is a free-format file containing one record per month:

Line 1	Title (station descriptor, etc.)
Line 2	Missing Value Code (must be a negative number)
Line 3.n	Daily Flows (one record per month)
	YY MM Q1 Q2 Q3 Q4 Q5 .... Qn, where n = # days in a month

Data records are free format, delimited by commas or spaces.

The program will read the appropriate number of days per line, depending upon specified year and month.

If Line 2 (missing value code) is omitted, all negative values in the flow file will be interpreted as missing.

The file 'CADDO.FLO' is an example of this format for daily flow records:

```
caddo_q.flo
-1
78 1 5.09 4.66 4.66   (etc. for 31 values)  18.29 15.81 13.42
78 2 11.72 10.51 9.73  (etc. for 28 values)  9.08 9.8
etc.
80 12 5.38 5.23  (etc.for 31 values)  4.35 4.25 4.13
```

*.WK1 Lotus-123 (Rel. 2.x) File Format for Sample Data

This spreadsheet format for sample data is indicated by the .WK1 extension. The layout is as follows:

```
ROW   A        B        C       D       E      F <-- COLUMN
1     Worksheet Title                            <-- title
2     STATION DATE     VAR1    VAR2    VAR3   etc.<-- labels (<=64)
3     sta1    01/01/86 10.0    20.                <-- data records
4     sta1    02/03/87 15.     23.     34.             "
5     sta2    01/02/86 23.     100.                    "
etc... (records contiguous)
```

The STATION field (optional) can be used to select data from a specific station. If included, STATION codes must be stored as character constants in COLUMN A of the worksheet. If the STATION column is excluded, FLUX will read all data from the file.

One field may refer to sample flows, others to concentrations (Example: VAR1 = flow, VAR1 = total p, VAR2 = ortho p, etc.) or to sample identifiers.

The Date label (Cell B2 in this example) must be DATE if dates are stored in Lotus format (days from January 1, 1990). The Date label must be YYMMDD if dates are stored in YYMMDD format (numeric values only).

The file 'CADDO_S.WK1' is an example of this format with the optional station field included and dates stored in Lotus format:

	A	B	C	D	E	F
1	degray inflow, flows in m3/sec					
2	Station	date	flow	tp	tdp	orthop
3	UK 456	01/23/78	3.61	28	22	13
4	UI568	09/29/81	3.01	24	17	12
5	XXXX	09/08/81	3.57	18	15	13
6	1234	04/24/78	26.59	42	36	22
7	Caddo	01/02/78	4.7	12	4	4
8	Caddo	01/09/78	4.39	11	10	4
9	Caddo	01/17/78	47	71		4
10	Other	03/06/78	7.92	25	25	12
11	Caddo	01/23/78	9.08	18		8
12	Caddo	01/30/78	16.3	19		
etc.						

The file 'CADDO_S1.WK1' is an example of this format with the optional station field excluded and dates stored in Lotus format:

	A	B	C	D	E	F
1	degray inflow, flows in m3/sec					
2	date	flow	tp	tdp	orthop	
3	01/02/78	4.7	12	4	4	
4	01/09/78	4.39	11	10	4	
5	01/17/78	47	71		4	
6	01/23/78	9.08	18		8	
7	01/30/78	16.3	19			

The file 'CADDO_S2.WK1' is an example of this format with the optional station field included and dates stored in YYMMDD format:

	A	B	C	D	E	F
1	degray inflow, flows in m3/sec - dates in yymmdd format					
2	Station	yymmdd	flow	tp	tdp	orthop
3	Caddo	780102	4.7	12	4	4
4	Caddo	780109	4.39	11	10	4
5	Caddo	780117	47	71		4
6	Caddo	780123	9.08	18		8

*.WK1 Lotus-123 (Rel. 2.x) File Format for Daily Flow Data

This spreadsheet format can be used for compact storage of flow data from multiple stations:

ROW	A	B	C	D	E	<-- COLUMN
1	Daily Flow Data Base					<-- title
2	DATE	STA1	STA2	STA3	etc.	<-- labels (<=64)
3	01/01/86	10.	20.			<-- data records
4	01/02/86	15.	23.	34.		"
5	01/03/86	23.	100.			"
etc...						

Columns B+ contain daily flow data from different stations.
(e.g., STA1 = flow data from station 1, STA2 = data from station 2)

If flow data are missing, omit the entire row or leave field blank.

DATE or FLOW fields can be formulas or numeric constants.

The file 'CADDO_Q.WK1' is an example of this format for daily flow records:

```
        A         B         C        D        E
1   degray daily flows in m3/sec
2   date         Caddo  Sta2    Sta3   etc...
3   01/01/78      5.09
4   01/02/78      4.66
5   01/03/78      4.66
6   01/04/78      4.66
7   01/05/78      4.66
etc...
```

*.IDX Format for Station Index

A separate index of station codes can be maintained on disk to facilitate reading of sample and flow data. The default extension of '*.IDX' is suggested to identify a station index file. A maximum of 63 stations can be indexed in a given file. An index file is accessed through the **Data/Read/Index** procedure. The format is as follows:

Line 1 Title (for user reference)
Line 2 Flow Scale Factor (default, can be modified when read)
Line 3 Concentration Scale Factor (" ")
Lines 4+ Station Record, fields enclosed in 'quotes'

Station Record Format:

Field	Description
1	station identifier (<= 8 characters)
2	sample station code (reference values in sample file)
3	sample file name
4	sample flow variable ('lookup' to retrieve from daily flow data)
5	flow station code (for .WK1 or .DAT data file types)
6	daily flow file
7	flow sign (+1 or -1) not enclosed in quotes

This is a free-format file with fields delimited by spaces or commas. All character strings must be enclosed in single quotes.

It is useful to create a separate index for each reservoir or group of stations in a common application.

The file 'CADDO.IDX' is an example:

```
'Station Index for Caddo R - Each Reads Equiv. Data from Different File Formats'
31.56        'Default Flow Scale Factor (except for *.FLX files)'
1            'Default Conc Scale Factor (except for *.FLX files)'
'Caddo1' ' '      'caddo.flx'     'flow'    ' '        'caddo.flx'      1
'Caddo2' ' '      'caddo_s.dat'   'flow'    ' '        'caddo_q.flo'    1
'Caddo3' ' '      'caddo_s.dat'   'flow'    'flow'     'caddo_q.dat'    1
'Caddo4'  'Caddo' 'caddo_s.wk1'   'flow'    'caDDo'    'caddo_q.wk1'    1
'Caddo5'  ' '     'caddo_s1.wk1'  'flow'    'CaddO'    'caddo_q.wk1'    1
'Caddo6'  'CADDO' 'caddo_s2.wk1'  'flow'    ' '        'caddo_q.flo'    1
'Caddo7'  'Caddo' 'caddo_s2.asc'  'fLOw'    ' '        'caddo_q.flo'    1
```

```
'Caddo8'  ' '     'caddo.flx'     'flow'    'flow'     'caddo_q.dat'     1
'Caddo9'  'Caddo' 'caddo_s.wk1'   'flow'    ' '        'caddo_q.flo'     1
'Caddo10' 'Caddo' 'caddo_s.wk1'   'flow'    'CADDO'    'caddo_q.wk1'     1
'Caddo11'  ' '    'caddo_s.dat'   'flow'    ' '        'caddo.flx'       1

Field 1     2          3            4       5            6           7
```

Once the station index file is created, the need to specify sample and flow data files on data-entry screens is eliminated. The user selects the desired station (Caddo1 thru Caddo11) from a menu and the remaining details are read from the index file.

This example illustrates the wide variety of options which are available for setting up FLUX input files. Each of the 'Stations' identified above 'Caddo1' through 'Caddo11' reads in exactly the same data by accessing files with different formats. In actual applications, each station would refer to a different location or data set. Examples of other *.IDX files are included on the program diskette.

FLUX Documented Session

This section demonstrates a typical FLUX session. As a training exercise, the user should be able to recreate this session by running FLUX and accessing the data files for Caddo River supplied with the program. Notes to the user are provided in italics below. Selected menu options are underlined. To begin, enter 'flux' at the prompt.

```
>FLUX
```

```
F  L  U  X

STREAM LOAD COMPUTATIONS
VERSION 4.5

Environmental Laboratory
USAE Waterways Experiment Station
Vicksburg, Mississippi

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PRESS KEY TO CONTINUE, <ESC> RETURN TO MENU                    100
```

A series of introductory screens appear. These contain brief descriptions of the program and summarize any new features not documented in this manual. To bypass these screens, press <Esc> *and the program menu will appear.*

```
F L U X  -  VERSION 4.5
Data     Calculate   Method   Plot   List   Utilities   Help   Quit
Read      Stratify    Delete    Composite    FlowSub    Title   List

     Read, Stratify, or List Data

MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
                                                  VARIABLE =
SAMPLE FILE =                                      STATION =
SAMPLES =    0, DATES =      0 to      0,    MEAN FLOW =          .00 HM3/YR
FLOW FILE =                                        FIELD =
FLOWS   =    0, DATES =      0 to      0,    MEAN FLOW =          .00 HM3/YR

MAX EVENT DURATION =  1 DAYS,  FLOW RESTRICTION = YES

      STRATUM:      1  EXCLU  TOTAL
SAMPLE COUNTS:      0      0      0
 EVENT COUNTS:      0      0      0
  FLOW COUNTS:      0      0      0

OUTPUT TO: SCREEN                                        CALC METHOD: Q WTD C
```

A one-line message describing the currently selected procedure appears at the bottom of the menu box. Characteristics of the current data set and program option settings are listed on the bottom half of the screen. Since no data set has been loaded, the above values are zeroes or blank.

Select **Data/Read/Index** *to read in a data set for Caddo River:*

```
                         F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read     Stratify     Delete    Composite     FlowSub     Title     List
Reset       Keep      Samples       Index

     Read Sample & Flow Data from Station Index File

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
  READ SAMPLE & FLOW DATA FROM STATION INDEX FILE

TITLE:                Caddo River

DOS PATH:             d:\coe\flux\caddo

STATION INDEX FILE:   caddo.idx

SCREENING VARIABLE:     RANGE: 0        TO 0

SAMPLE DATE RANGE: >= 0        < 0       (YYMMDD)

FLOW DATE RANGE:   >= 0        < 0       (YYMMDD)

SEASON RANGE:      >= 0        < 0       (MMDD)

          station index file name                          F8=HELP/FIELD
F1=HELP,  F2=DONE/SAVE,  F3=EDIT FIELD,  F7=HELP/EDITOR,  <ESC>=ABORT
```

The program reads the station index file 'caddo.idx' and lists the indexed stations. As discussed in the Data File Formats section, this example index file illustrates a variety of data set configurations all accessing the same data. In practice, users can create separate index files to facilitate access to data for different stations within a given project or reservoir. Caddo1 is selected here. Date or season limits can be entered on this screen. Press **<F2>** *to proceed.*

```
  FIELD
> Caddo1
  Caddo2
  Caddo3
  Caddo4
  Caddo5
  Caddo6
  Caddo7
  Caddo8
  Caddo9
  Caddo10
  Caddo11
```

Sample and flow files for the selected station are opened. The program reads the file headers and asks the user to select the variable to be analyzed (total p) from a list of all fields contained in the sample file.

```
Locating Sample File....
OPENING SAMPLE FILE = caddo.flx
```

```
  FIELD
  flow
> total p
  total dp
  ortho p
```

```
DEFINE FIELD FOR: CONCENTRATION
Locating Sample File....
OPENING SAMPLE FILE = caddo.flx
SAMPLE CONCENTRATION FIELD = total p
CONCENTRATION UNITS FACTOR =        1.000000
Define Flow Scale Factor
Scale Factor ?  < 31.5600    > ?
Define Concentration Scale Factor for: total p
Scale Factor ?  < 1.00000    > ?
Flow Scale Factor =     31.5600
Conc Scale Factor =      1.0000
Reading Samples...
degray inflow, Jan 78 - Dec 80 - flows in cms
NUMBER OF SAMPLES =        168
Reading Flows...
OPENING FLOW FILE = caddo.flx
degray inflow, Jan 78 - Dec 80 - flows in cms
NUMBER OF FLOW RECORDS =       1096
<H>
```

Sample and flow counts are listed as the data files are read. The Scale Factor prompts permit user to change default scale factors stored in the station index file. Press **<Enter>** *to accept default values.*

```
Caddo River                          VAR=total p   METHOD= 2 Q WTD C
TABULATION OF MISSING DAILY FLOWS:
Flow File =caddo.flx                        ,   Station =
Daily Flows from 780101 to 801231
Summary:
Reported Flows = 1096
Missing Flows =     0
Zero Flows =        0
Positive Flows = 1096
<EOF>
```

An inventory of daily flows is presented, including date range, missing values, and zero values. Any flow records out of sequence would also be listed here. Control returns to the main menu.

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read     Stratify     Delete    Composite     FlowSub     Title     List

     Read and/or Stratify Data

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
Caddo River                                    VARIABLE = total p
SAMPLE FILE = caddo.flx                        STATION =
SAMPLES =  168, DATES = 780102 to 810929,   MEAN FLOW =      405.16 HM3/YR
FLOW FILE = caddo.flx                            FIELD =
FLOWS   = 1096, DATES = 780101 to 801231,   MEAN FLOW =      413.59 HM3/YR

MAX EVENT DURATION =  1 DAYS,  FLOW RESTRICTION = YES


      STRATUM:       1  EXCLU  TOTAL
SAMPLE COUNTS:     168      0    168
 EVENT COUNTS:     168      0    168
  FLOW COUNTS:    1096      0   1096
OUTPUT TO: SCREEN                                    CALC METHOD: Q WTD C
```

The bottom half of the screen summarizes the current case data. Sample data can be listed using the **Data/List/Samples** *procedure:*

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read     Stratify     Delete    Composite     FlowSub     Title     List
Samples   Flows   Samples

     List Sample Data

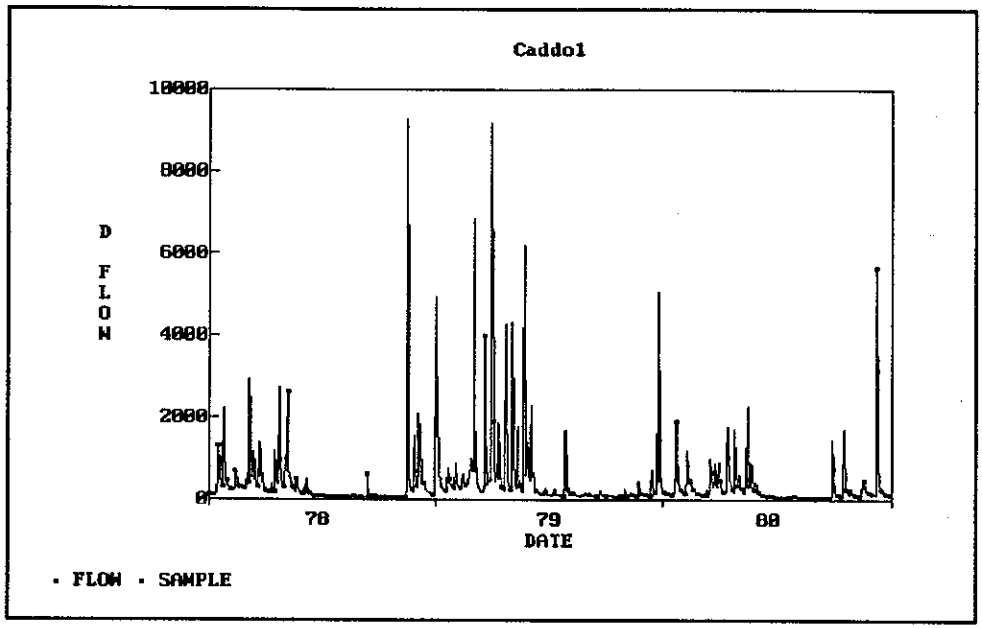
 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
Caddo River                          VAR=total p   METHOD= 2 Q WTD C
SAMPLE  DATE  EVENT STRATUM  DAILY-FLOW SAMPLE-FLOW   CONC        FLUX
    1 780102      1       1     147.07     148.33    12.00      1779.98
    2 780109      2       1     142.97     138.55    11.00      1524.03
    3 780117      3       1    1313.53    1483.32    71.00    105315.70
  etc...
     USE KEYPAD, <F1>=HELP, <F8>=SAVE, <ESC>=QUIT  OUTPUT
```

Both daily mean flows and sample flows are listed along with sample concentrations. The listing extends beyond the bottom of the screen. Use the keypad arrows to forward or backward through the file. The listing can be saved on disk by pressing **<F8>**. *Press* **<Esc>** *to continue.*

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc   Load   Flow   Daily   Qfreq   Residuals   GridOpt
Date       Month       Histogram
1Linear       2Log       3Filled
     Plot Daily Flows (hm3/yr) vs. Date - Linear Scale

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```



*Plotting the daily flow record (***Plot/Daily/Date/Linear***) shows hydrograph features and the dates of sample collection (squares). Note that relatively few high-flow samples were collected during the high-runoff period in late 1978 to early 1979. The square symbols indicate the daily flows on the dates of sample collection (not the sample flows).*

The **Calculate/Compare** *procedure provides a more quantitative comparison of sample and total flow distributions.*

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Compare   Loads   Series
     Compare Sample and Total Flow Distributions
```

```
Comparison of Sampled & Total Flow Distributions
        ------ SAMPLED -----        ------- TOTAL ------
STRAT   N     MEAN   STD DEV      N     MEAN   STD DEV     DIFF     T PROB(>T)
  1    168   405.16   795.10   1096   413.59   781.02    -8.43     .13    .894
***    168   405.16   795.10   1096   413.59   781.02    -8.43     .13    .894

Average Sample Interval =   8.1 Days, Date Range = 780102 to 810929
Maximum Sample Interval =    41 Days, Date Range = 790123 to 790306
Percent of Total Flow Volume Occurring In This Interval =   6.4%

Total Flow Volume on Sampled Days =      47003.2 hm3
Total Flow Volume on All Days     =     453292.5 hm3
Percent of Total Flow Volume Sampled =    10.4%

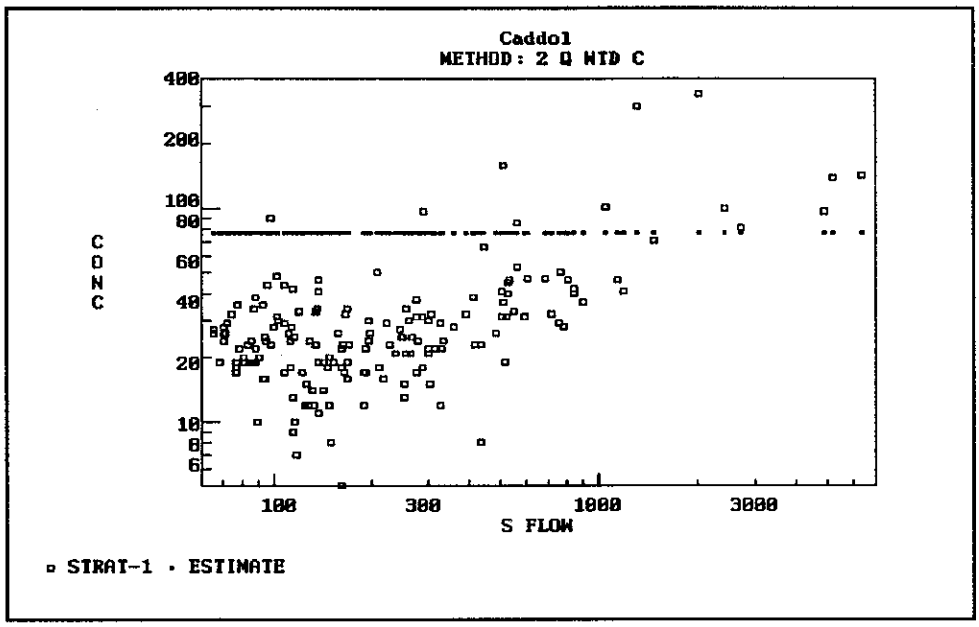
Maximum Sampled Flow Rate =     6406.68 hm3/yr
Maximum Total Flow Rate   =     9305.78 hm3/yr
Number of Days when Flow Exceeded Maximum Sampled Flow =  4 out of 1096

Percent of Total Flow Volume Occurring at Flow Rates Exceeding the
      Maximum Sampled Flow Rate =     7.1%
```

The last statistic indicates that the high-flow regimes are not represented very well in this case. This is consistent with impressions derived above from the

daily flow plot. Plotting concentration against flow is generally appropriate here.

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart  Conc   Load   Flow   Daily   Qfreq   Residuals   GridOpt
Flow      Date       Month      Estimated       Histogram
     Plot Sample Concentration vs. Sample Flow
```

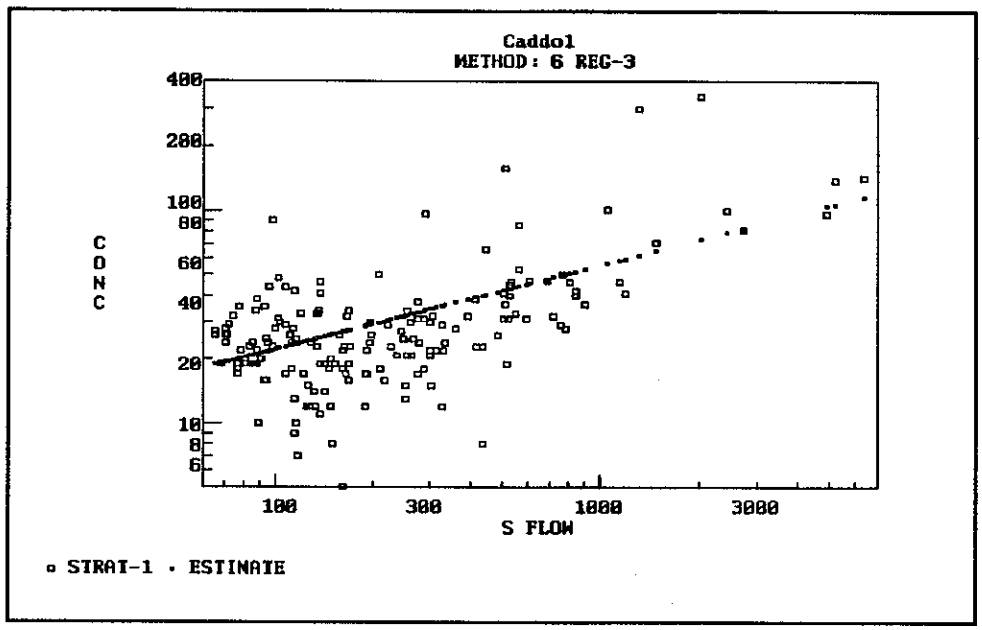


Concentration increases with flow. Since the data are not stratified and **Method 2** *is selected, the predicted concentration is constant. Regression methods attempt to represent concentration variations with flow within each stratum. This can be demonstrated by selecting* **Method 6** *and replotting.*

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
1 AVG LOAD     2 Q WTD C     3 IJC     4 REG 1     5 REG 2     6 REG 3

     Method 6 - Regression Model 2 - log(c) vs. Log(Q) separate
```

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart  Conc   Load   Flow   Daily   Qfreq   Residuals   GridOpt
Flow      Date       Month      Estimated       Histogram
     Plot Sample Concentration vs. Sample Flow
```



When **Method 6** *is selected, the predicted concentration varies with flow. Some nonlinearity is evident. Concentrations are underpredicted at high flows. This suggests that more flow strata are needed to capture the flow/ concentration relationship.*

The following sequence demonstrates the effects of stratifying the data on the load estimates. **Loads** *are first calculated without stratification.* **Method 2** *is reselected.*

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
1 AVG LOAD    2 Q WTD C    3 IJC    4 REG 1    5 REG 2    6 REG 3
     Method 2 - Flow-Weighted-Mean Conc.
```

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Compare    Loads    Series
     Calculate Loads Using Each Method
```

```
Caddo River                    VAR=total p   METHOD= 2 Q WTD C
COMPARISON OF SAMPLED AND TOTAL FLOW DISTRIBUTIONS
STR       NQ  NC  NE  VOL%   TOTAL FLOW SAMPLED FLOW   C/Q SLOPE SIGNIF
 1      1096 168 168 100.0      413.588      405.163        .396   .000
***     1096 168 168 100.0      413.588      405.163

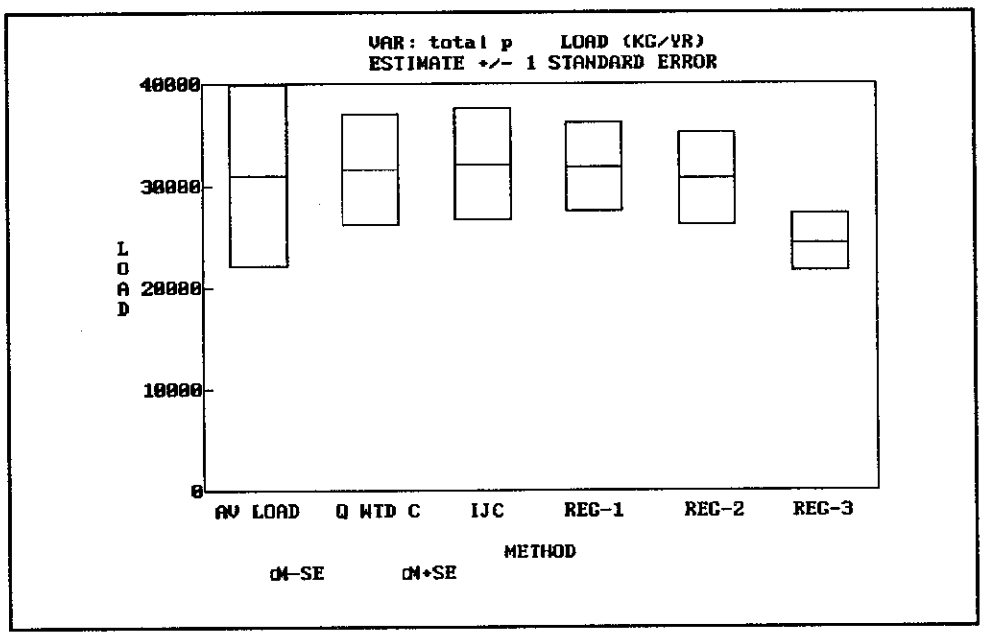
FLOW STATISTICS
FLOW DURATION =    1096.0 DAYS  =  3.001 YEARS
MEAN FLOW RATE =   413.588 HM3/YR
TOTAL FLOW VOLUME =    1241.05 HM3
FLOW DATE RANGE    = 780101 TO 801231
SAMPLE DATE RANGE = 780102 TO 810929
```

METHOD	MASS (KG)	FLUX (KG/YR)	FLUX VARIANCE	CONC (PPB)	CV
1 AV LOAD	93253.1	31077.3	.7923E+08	75.14	.286
2 Q WTD C	95192.3	31723.5	.2872E+08	76.70	.169
3 IJC	96738.0	32238.7	.2913E+08	77.95	.167
4 REG-1	95971.5	31983.2	.1927E+08	77.33	.137
5 REG-2	92308.6	30762.5	.2024E+08	74.38	.146
6 REG-3	73497.2	24493.5	.7845E+07	59.22	.114

<EOF>

Results (both the load estimate and CV) for Method 6 are somewhat lower than results for the other calculation methods. Results for Methods 1-5 are within a relatively narrow range. This is shown graphically using the **Plot/ Barchart** *procedure:*

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart    Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
Load        Mass        Concs        Flow
Method        Stratum
     Plot Load Estimates (kg/yr) vs. Calculation Method
```



We will now try stratifying the data using 2 flow intervals.

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read    Stratify    Delete    Composite    FlowSub    Title    List
Flow        General        Reset        List
2 Strata        3 Strata        4 Strata        Other
     2 Flow Strata - Boundary at QMEAN
```

```
          STRATIFY BASED UPON FLOW
              UNITS =  HM3/YEAR

      MEAN FLOW:        413.588
      MAXIMUM FLOW:     9305.78

                                  SAMPLE      FLOW
STRATUM  UPPER FLOW LIMIT          COUNT     COUNT

   1     <  413.588                   0         0

   2     <  10236.3                   0         0

   3     <  0                         0         0

   4     <  0                         0         0

   5     <  0                         0         0

        < upper flow bound for stratum 1 (hm3/yr)
F1=HELP,  F2=DONE/SAVE,  F3=EDIT FIELD,  F7=HELP/EDITOR,  <ESC>=ABORT
```

The values shown on the edit screen are automatically calculated from the total flow distribution. These can be edited at this point. Press **<F2>** *when you are done editing or to accept the default values. An inventory of sample counts and flow values in each stratum is listed:*

```
Caddo River                          VAR=total p   METHOD= 2 Q WTD C
STRATIFICATION SCHEME:
       -- DATE --    -- SEASON --   -------- FLOW --------
STR  >=MIN  < MAX  >=MIN  < MAX        >=MIN       < MAX
  1      0      0      0      0          .00      413.59
  2      0      0      0      0       413.59    10236.36

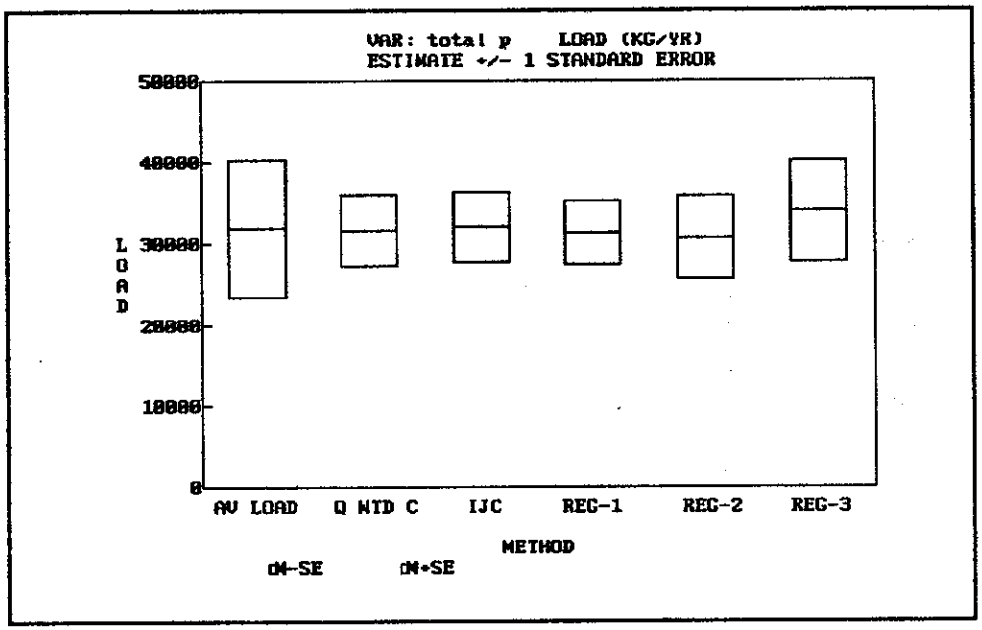
STR   SAMPLES    EVENTS     FLOWS  VOLUME %
  1       129       129       833     31.56
  2        39        39       263     68.44
EXCLUDED    0         0         0       .00
   TOTAL  168       168      1096    100.00
```

Now repeat the concentration versus flow plot:

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc   Load   Flow   Daily   Qfreq   Residuals   GridOpt
Flow       Date       Month       Estimated       Histogram

     Plot Sample Concentration vs. Sample Flow
```

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart    Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
Load        Mass        Concs        Flow
Method        Stratum
     Plot Load Estimates (kg/yr) vs. Calculation Method
```



Estimates for all methods have converged. This is a desired result. Now try 3 flow strata to see whether precision can be improved.

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read    Stratify    Delete    Composite    FlowSub    Title    List
Flow    General    Reset    List
2 Strata    3 Strata    4 Strata    Other
     3 Flow Strata - Boundaries at QMEAN/2, QMEAN x 2
```

STRATIFY BASED UPON FLOW
UNITS = HM3/YEAR

MEAN FLOW: 413.588
MAXIMUM FLOW: 9305.78

STRATUM	UPPER FLOW LIMIT	SAMPLE COUNT	FLOW COUNT
1	< 206.794	0	0
2	< 827.176	0	0
3	< 10236.3	0	0
4	< 0	0	0
5	< 0	0	0

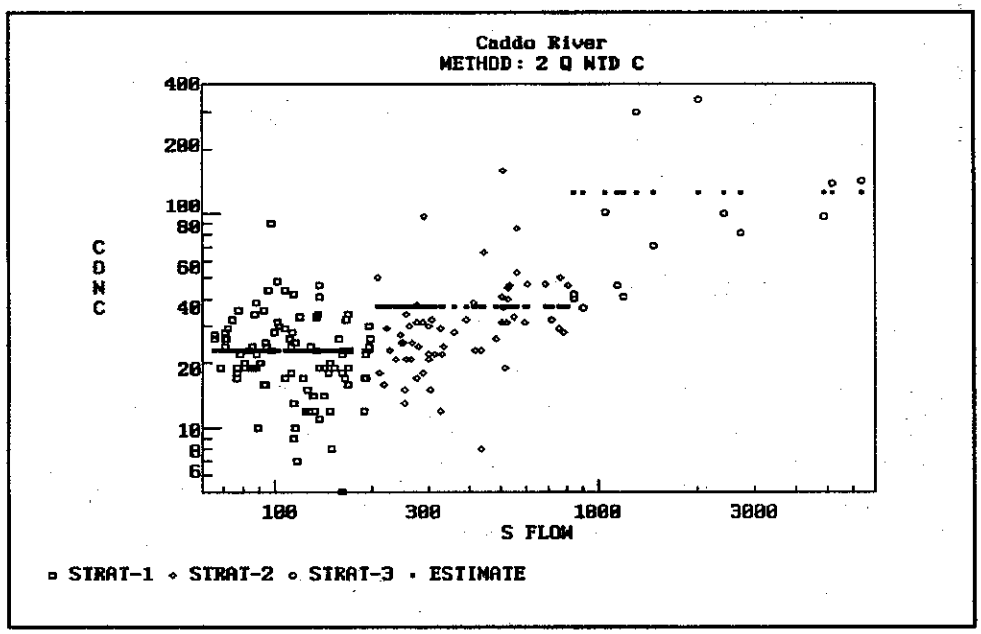
Caddo River VAR=total p METHOD= 2 Q WTD C

```
STRATIFICATION SCHEME:
       -- DATE --    -- SEASON --   -------- FLOW --------
STR  >=MIN  < MAX  >=MIN  < MAX        >=MIN       < MAX
  1      0      0      0      0          .00      206.79
  2      0      0      0      0       206.79      827.18
  3      0      0      0      0       827.18    10236.36

STR   SAMPLES    EVENTS     FLOWS  VOLUME %
  1        93        93       582     15.44
  2        61        61       407     35.68
  3        14        14       107     48.88
EXCLUDED    0         0         0       .00
   TOTAL  168       168      1096    100.00
<H>
```

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart    Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
Flow        Date        Month        Estimated        Histogram

     Plot Sample Concentration vs. Sample Flow
```



Using 3 flow strata provides a better fit of the flow/concentration relationship.

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Compare    Loads    Series
     Calculate Loads Using Each Method
```

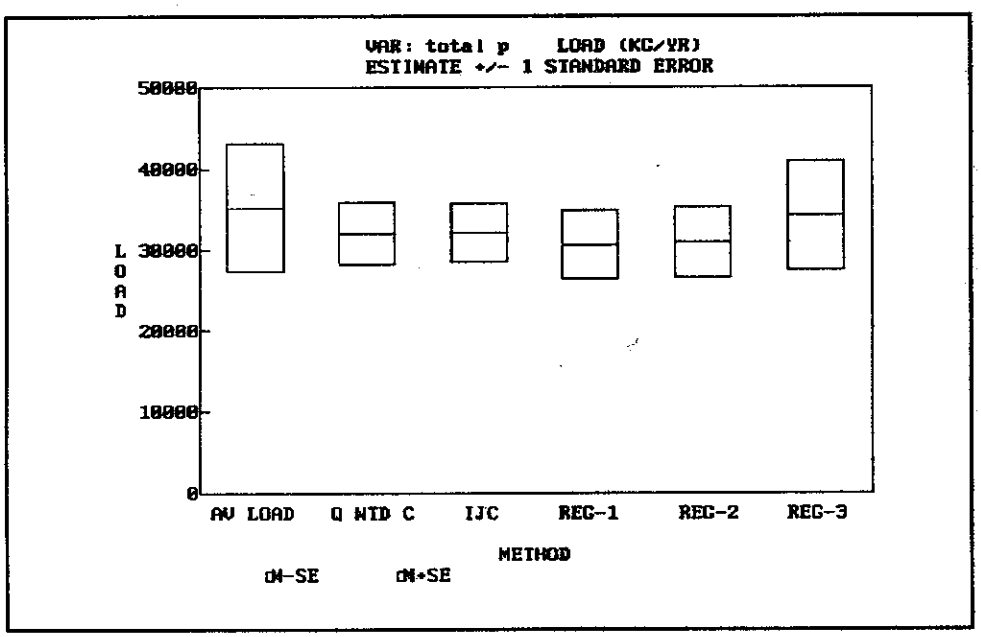
```
Caddo River                          VAR=total p   METHOD= 2 Q WTD C
COMPARISON OF SAMPLED AND TOTAL FLOW DISTRIBUTIONS
STR        NQ  NC  NE  VOL%   TOTAL FLOW SAMPLED FLOW   C/Q SLOPE SIGNIF
 1        582  93  93  15.4     120.233      119.816       -.316   .035
 2        407  61  61  35.7     397.424      399.808        .543   .001
 3        107  14  14  48.9    2070.698     2324.010        .515   .064
***      1096 168 168 100.0     413.588      405.163
```

```
FLOW STATISTICS
FLOW DURATION =     1096.0 DAYS  =  3.001 YEARS
MEAN FLOW RATE =   413.588 HM3/YR
TOTAL FLOW VOLUME =     1241.05 HM3
FLOW DATE RANGE    = 780101 TO 801231
SAMPLE DATE RANGE = 780102 TO 810929
```

METHOD	MASS (KG)	FLUX (KG/YR)	FLUX VARIANCE	CONC (PPB)	CV
1 AV LOAD	105913.8	35296.5	.6190E+08	85.34	.223
2 Q WTD C	96537.5	32171.8	.1432E+08	77.79	.118
3 IJC	96872.4	32283.4	.1304E+08	78.06	.112
4 REG-1	92095.1	30691.4	.1783E+08	74.21	.138
5 REG-2	93187.2	31055.3	.1890E+08	75.09	.140
6 REG-3	102935.2	34303.9	.4579E+08	82.94	.197

Precision has improved. The CV for Method 2 is down to 0.118.

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart    Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
Load        Mass        Concs        Flow
Method        Stratum
     Plot Load Estimates (kg/yr) vs. Calculation Method
```



The methods are still convergent. Now try 4 flow strata.

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read    Stratify    Delete    Composite    FlowSub    Title    List
Flow    General    Reset    List
2 Strata    3 Strata    4 Strata    Other
     4 Flow Strata - Boundaries at QMEAN/2, QMEAN*2, QMEAN*8
```

```
          STRATIFY BASED UPON FLOW
              UNITS =  HM3/YEAR

      MEAN FLOW:        413.588
      MAXIMUM FLOW:     9305.78

                                        SAMPLE      FLOW
  STRATUM  UPPER FLOW LIMIT              COUNT     COUNT

     1     <  206.794                       0         0

     2     <  827.176                       0         0

     3     <  3308.70                       0         0

     4     <  10236.3                       0         0

     5     <  0                             0         0
```

Caddo River VAR=total p METHOD= 2 Q WTD C

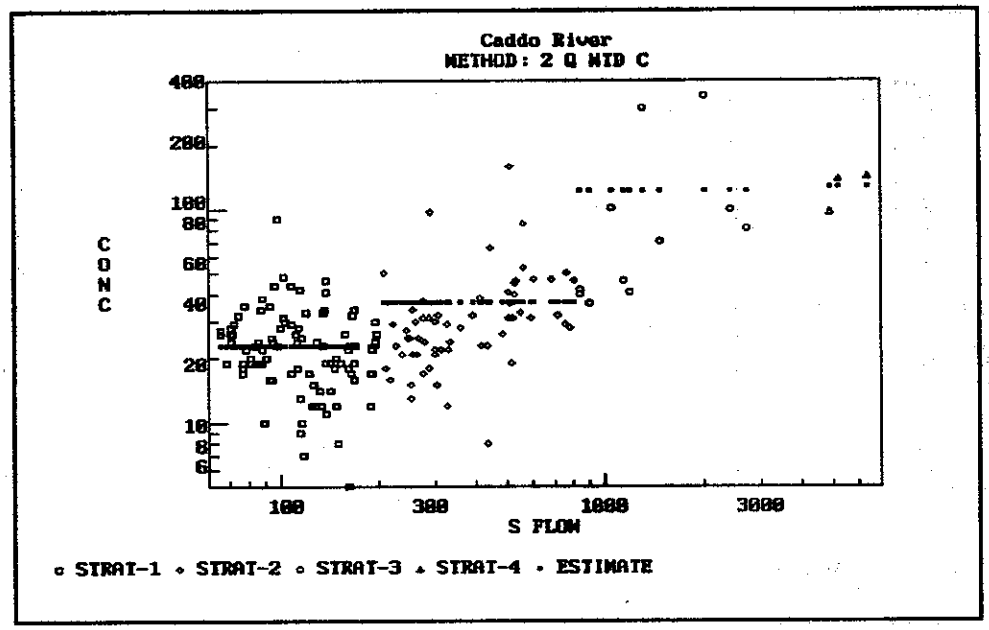
STRATIFICATION SCHEME:

	-- DATE --		-- SEASON --		-------- FLOW --------	
STR	>=MIN	< MAX	>=MIN	< MAX	>=MIN	< MAX
1	0	0	0	0	.00	206.79
2	0	0	0	0	206.79	827.18
3	0	0	0	0	827.18	3308.70
4	0	0	0	0	3308.70	10236.36

STR	SAMPLES	EVENTS	FLOWS	VOLUME %
1	93	93	582	15.44
2	61	61	407	35.68
3	11	11	89	27.53
4	3	3	18	21.35
EXCLUDED	0	0	0	.00
TOTAL	168	168	1096	100.00

```
                    F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc   Load   Flow   Daily   Qfreq   Residuals   GridOpt
Flow       Date       Month       Estimated       Histogram

     Plot Sample Concentration vs. Sample Flow
```



The highest flow stratum (4) now contains only three samples. This is not a desirable situation.

```
F L U X - VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Compare    Loads    Series
     Calculate Loads Using Each Method
```

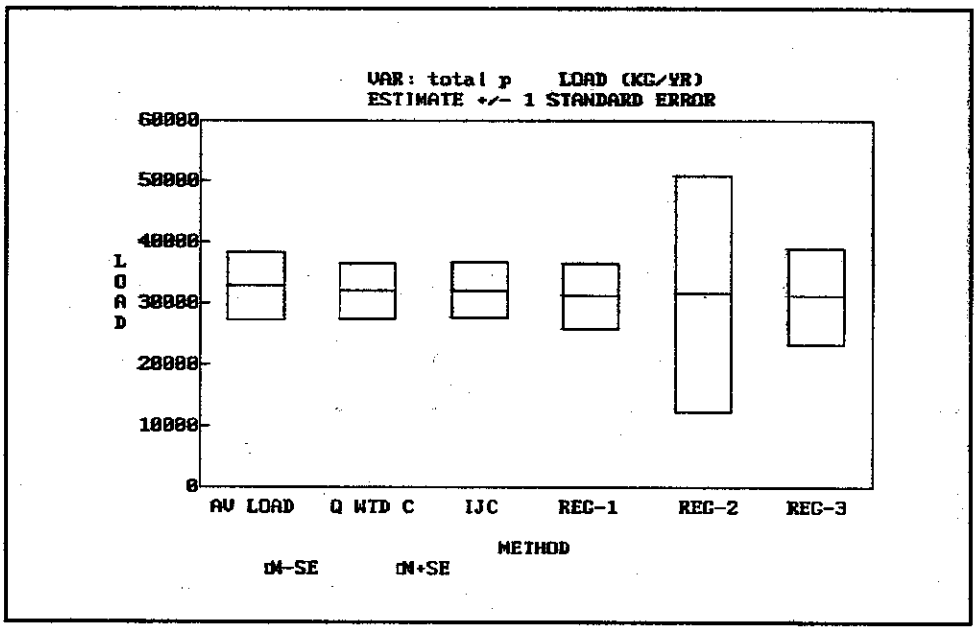
```
Caddo River                          VAR=total p   METHOD= 2 Q WTD C
COMPARISON OF SAMPLED AND TOTAL FLOW DISTRIBUTIONS
STR       NQ  NC  NE  VOL%   TOTAL FLOW SAMPLED FLOW   C/Q SLOPE SIGNIF
 1       582  93  93  15.4      120.233      119.816      -.316   .035
 2       407  61  61  35.7      397.424      399.808       .543   .001
 3        89  11  11  27.5     1402.069     1450.153      1.011   .087
 4        18   3   3  21.4     5376.702     5528.155      1.165   .467
***     1096 168 168 100.0      413.588      405.163

FLOW STATISTICS
FLOW DURATION =    1096.0 DAYS  =  3.001 YEARS
MEAN FLOW RATE =   413.588 HM3/YR
TOTAL FLOW VOLUME =    1241.05 HM3
FLOW DATE RANGE   = 780101 TO 801231
SAMPLE DATE RANGE = 780102 TO 810929

METHOD          MASS (KG)   FLUX (KG/YR)  FLUX VARIANCE CONC (PPB)      CV
1 AV LOAD         98784.8       32920.7      .2992E+08      79.60    .166
2 Q WTD C         96312.5       32096.8      .1965E+08      77.61    .138
3 IJC             96872.1       32283.3      .1999E+08      78.06    .139
4 REG-1           93773.0       31250.5      .2775E+08      75.56    .169
5 REG-2           95141.0       31706.4      .3722E+09      76.66    .608
6 REG-3           93901.5       31293.4      .6185E+08      75.66    .251
```

The CV values using 4 flow strata have increased relative to results for 3 flow strata. This suggests that the sampling intensity is not sufficient to support 4 strata.

```
F L U X - VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart   Conc   Load   Flow   Daily   Qfreq   Residuals   GridOpt
Load       Mass       Concs       Flow
Method       Stratum
     Plot Load Estimates (kg/yr) vs. Calculation Method
```



The load estimates from each method are in reasonable agreement. Convergence of load estimates as the number of strata increases is a desired result. The following table summarizes the effect of increasing the number of flow strata on the estimated flow-weighted mean concentration for Method 2:

Number of Strata	*Flow-Weighted-Mean*	*CV*
1	*76.7*	*.169*
2	*76.5*	*.139*
3	*77.8*	*.118*
4	*77.6*	*.138*

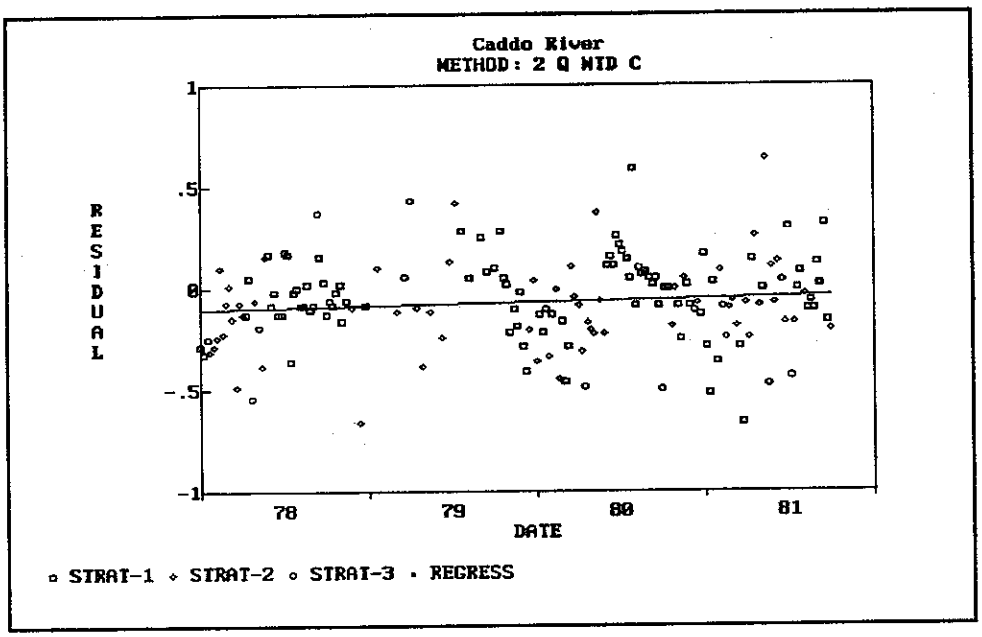
The mean estimates did not change significantly, and the error CV was lowest for 3 strata. The increase in error at 4 strata reflects data limitations (only three samples in flow interval 4). This causes instability, particularly in the regression methods (4-6), when 4 strata are used. Based upon these results, the load estimate based upon 3 flow strata and Method 2 is selected. This could be further refined by adjusting the flow strata boundaries (using the **Data/Stratify/Flow/Other** *procedure) to obtain a better C/Q fit and reduce the CV estimate.*

We can reset the stratification scheme to 3 flow strata and examine residuals.

```
F L U X - VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Read    Stratify     Delete    Composite    FlowSub    Title    List
Flow    General      Reset     List
2 Strata    3 Strata    4 Strata    Other
    3 Flow Strata - Boundaries at QMEAN/2, QMEAN x 2
```

```
F L U X - VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart    Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
Flow    Date    Month    Estimated    Histogram    Autocorr

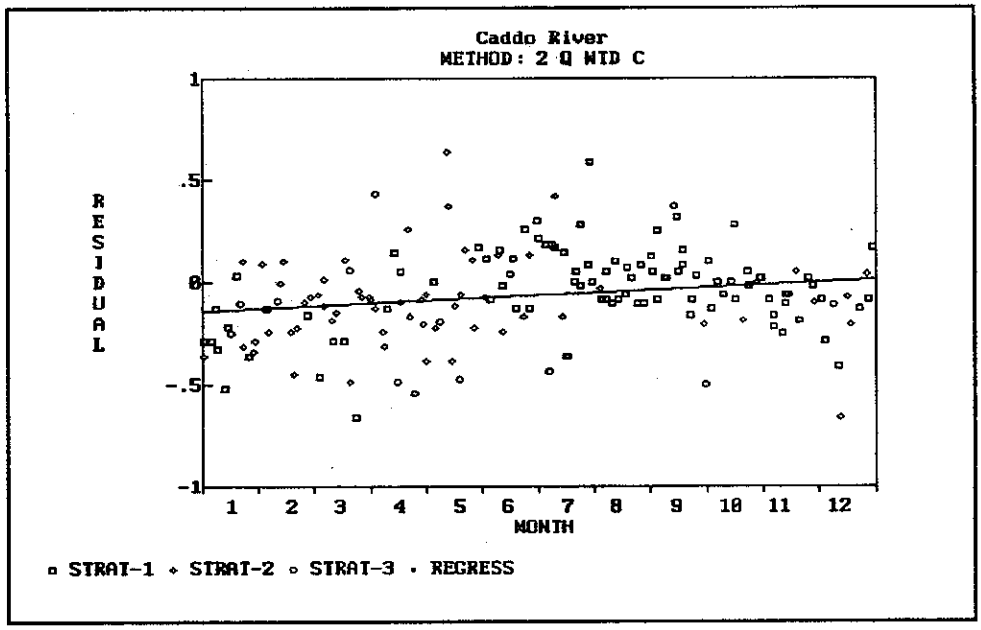
    Plot Residuals vs. Date
```



This plot can be used to test for trend, i.e., increasing or decreasing concentrations, adjusted for variations in flow. Generally, several years of monitoring data collected over a wide range of flow regimes are required in order to make a reliable test for trend. Stratification based upon date may be appropriate if significant trend or step change is apparent. An alternative approach would be to estimate loads separately for different time periods by specifying appropriate date ranges in the **Data/Read** *procedures.*

```
F L U X - VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Barchart    Conc    Load    Flow    Daily    Qfreq    Residuals    GridOpt
Flow    Date    Month    Estimated    Histogram    Autocorr

    Plot Residuals vs. Month
```



This plot can be used to test for seasonality. If significant seasonal patterns in the residuals are evident, stratification based upon season may be appropriate. This is accomplished by using the **Data/ Stratify/General** *procedure. Now examine the load breakdown by flow stratum.*

```
F L U X  -  VERSION 4.5
Data    Calculate    Method    Plot    List    Utilities    Help    Quit
Residuals        Breakdowns        Jackknife
     List Load & Flow Breakdowns by Stratum; Optimal Sample Alloc.
```

Caddo River VAR=total p METHOD= 2 Q WTD C

FLUX Breakdown by Stratum:

ST	NS	NE	FREQ DAYS	FLOW HM3/YR	FLUX KG/YR	VOLUME HM3	MASS KG	CONC PPB	CV -
1	93	93	582.0	120.23	2761.4	191.58	4400.1	23.0	.050
2	61	61	407.0	397.42	14501.1	442.85	16158.7	36.5	.092
3	14	14	107.0	2070.70	259357.2	606.61	75978.7	125.3	.148
***	168	168	1096.0	413.59	32171.8	1241.05	96537.5	77.8	.118

Optimal Sample Allocation:

ST	NS	NE	NE%	NEOPT%	FREQ%	VOL%	MASS%	VAR%	VARIANCE	CV
1	93	93	55.4	3.8	53.1	15.4	4.6	.0	.5276E+04	.050
2	61	61	36.3	20.8	37.1	35.7	16.7	1.7	.2442E+06	.092
3	14	14	8.3	75.5	9.8	48.9	78.7	98.3	.1407E+08	.148
***	168	168	100.0	100.0	100.0	100.0	100.0	100.0	.1432E+08	.118

Optimal Allocation of 168 Sampled Events Across Strata (According to NEOPT%)
Would Reduce CV of FLUX Estimate from 0.118 to 0.045

The top part of the table shows the distribution of flow, flux, volume, and mass across flow strata. The middle part of the table lists the distribution of sampling effort, flow days, flow volume, mass, and error variance, each expressed as percentage of the total. The bottom part of the table estimates the potential benefit of optimizing the sample allocation across strata to obtain the lowest error variance for a fixed number of sampling events.

NE% = percent of total sample events in stratum
NEOPT% = optimal percent of total sample events in stratum

The reduction in error CV attributed to shifting from the current sample distribution (NE%) to the optimal distribution (NEOPT%) is listed. This can be used to refine future monitoring program designs.

In this example, 98.3 percent of the variance in the load estimate is attributed to the Stratum 3. This received only 8.3 percent of the sampling effort (NE%). An optimal sampling design would devote 75.5 percent of the effort to Stratum 3. The optimal design would reduce the error CV from 0.118 to 0.045.

3 PROFILE

PROFILE Overview

PROFILE is an interactive program designed to assist in the analysis and reduction of pool water quality measurements. The user supplies a data file containing basic information on the morphometry of the reservoir, monitoring station locations, surface elevation record, and water quality monitoring data referenced by station, date, and depth. The program's functions are in three general areas:

a. Display of concentrations as a function of elevation, location, and/or date.

b. Calculation of mixed-layer summary statistics and standard errors.

c. Calculation of hypolimnetic and metalimnetic oxygen depletion rates from temperature and oxygen profiles.

These applications are introduced in the following paragraphs. Details are given in subsequent sections.

Several display formats support exploratory analysis of reservoir water quality data. These elucidate important spatial and temporal variance components. Reviewing these displays can help the user in evaluating data adequacy, designing future monitoring programs, and specifying appropriate segmentation schemes for modeling. The various display formats and options are described in detail in the Program Operation section and demonstrated in the Documented Session section of this chapter.

Mixed-layer water quality data can be summarized in a two-way table format that depicts variations as a function of space (station or reservoir segment) and time (sampling date) over date, depth, and station ranges specified by the user. In the two-way analysis, filtering and weighing algorithms are used to generate robust summary statistics (median, mean, and coefficient of variation of the mean) for characterization of reservoir trophic status, evaluations of data adequacy, and application of BATHTUB (Chapter 4) or other empirical models.

Hypolimnetic oxygen depletion rates are important symptoms of eutrophication in stratified reservoirs. Using input oxygen and temperature profiles, the program applies interpolation and area-weighing procedures to calculate depletion rates. Graphic and tabular outputs assist the user in selecting appropriate sampling dates and thermocline boundaries for oxygen depletion calculations.

The following sections of this chapter describe:

a. Input data requirements.

b. Application procedures.

c. Program operation.

d. Input data file format.

e. Data-entry screens.

f. Documented session.

Input Data Requirements

PROFILE requires an input file containing data in the following groups:

Group 1: Title
Group 2: Parameters and Unit Conversion Factors
Group 3: Reservoir Morphometry
Group 4: Component Key (water quality variables)
Group 5: Station Key (monitoring locations)
Group 6: Elevation Data (reservoir surface elevations)
Group 7: Profile Data (water quality measurements)

All of this information can be specified in a single, fixed-format ASCII file, as described in the section entitled Input Data File Format. As an option, water quality measurements (Group 7) can also be read from spreadsheet files or free-format ASCII files.

Group 2 contains scale factors to convert input area, elevation, and depth units to metric units used by the program (square kilometers for area and meters for elevation and depth). Missing concentration values are flagged with a special code specified in Group 2. The "date blocking factor" is used to combine data for summary purposes. In large reservoirs, it may be difficult to sample all pool monitoring stations in 1 day. If a blocking factor of 2 is specified, for example, sample dates differing by $<=2$ days will be associated with the same sampling round for data-summary purposes.

Group 3 contains an elevation versus surface area table for the reservoir. This information is used only in computing areal hypolimnetic oxygen depletion rates.

Group 4 defines water quality components and concentrations interval for contour plotting. In eutrophication studies, the input file would normally contain measurements of oxygen, temperature, total phosphorus, ortho phosphorus, inorganic nitrogen, organic nitrogen, total nitrogen, chlorophyll *a*, and Secchi depth. Output is formatted to provide one place to the right of the decimal point; thus, input units should be milligrams per cubic meter (or parts per billion) for nutrients and chlorophyll *a* and meters for Secchi depth. Other components should be scaled accordingly. Groups 4 and 7 can contain up to 64 water quality components. A maximum of 10 water quality components can be read from disk files and analyzed in a given session.

Integers (range 01-15) are used to identify sampling stations and are cross-referenced to user-defined station codes and descriptions in Group 5. To facilitate interpretation of data displays and tables, station numbers should be assigned in a logical order (e.g., upstream or downstream order within each tributary arm). The optional "river kilometer" input for each station would normally represent the distance along the thalweg from the reservoir inflow; since the river kilometer index is used only for spatial display purposes, any frame of reference can be used.

In computing summary statistics, "segment numbers" specified in Group 5 can be used to combine data from specific stations based upon their relative proximities, major tributary arms, horizontal mixing characteristics, etc. For example, if the file contains two adjacent stations (or two stations with similar observed water quality), data from these stations can be grouped by assigning them the same segment number. Segment numbers can refer directly to the spatial segments used in reservoir modeling (see BATHTUB). If oxygen depletion calculations are not desired, it is also possible to use segment numbers to refer to stations in different reservoirs.

"Areal weights" specified in Group 5 are used in calculating area-weighted summary statistics over the entire reservoir and should reflect the approximate surface area represented by each station. These can be estimated by plotting stations on a reservoir map and allocating a given area to each station, based upon relative station locations and bisecting lines between adjacent stations. Since they are rescaled in calculations, the weighing factors do not have to sum to 1.0.

Group 6 contains daily measurements of reservoir surface elevation over the period of water quality measurements. The program uses this information in generating concentration versus elevation plots and in calculating hypolimnetic oxygen depletion rates. Only the elevations on sampling dates are used; thus, the entire daily elevation record is not required. If an elevation value is not specified for a particular sampling date, it is estimated by interpolation from adjacent dates with specified elevation values.

PROFILE can handle problems with the following maximum dimensions:

Elevation/Area pairs	=	29
Number of stations	=	50
Number of samples	=	2,500
Number of water quality components	=	10
Number of sample dates	=	250
Number of measurements	=	12,000

Water quality records must specify the station, date, and depth, in addition to measurements. If the depth field is missing, a sample depth of 0 is assumed. Note that limitations on sample numbers and number of water quality components apply only to data read into the computer memory at the time of program execution, not to the data file itself. Since the user is prompted for the ranges of station numbers, sample years, and water quality components to be considered in a given run, the data file can be much larger than indicated above (except for the maximum number of stations). Users should check the online documentation file (accessed through the HELP menu) for maximum problem dimensions or other program changes in updated versions of PROFILE (Version 4.5 is documented here).

Mixed-Layer Water Quality Data Summary

A major function of PROFILE is the calculation of mixed-layer, summary statistics for characterization of reservoir trophic status, evaluations of data adequacy and monitoring program designs, and application of empirical models. Calculation steps (outlined in the Documented Session section) include the following:

a. Setting the data window to include mixed-layer samples.

b. Generating box plots to depict spatial and temporal variations.

c. Summarizing the data in a two-way table format.

These steps are described below.

The data window defines the ranges of stations, dates, and depths to be included in displays and statistical summaries. For characterization of reservoir trophic status, the window would normally be set to include all stations, dates in the growing season (e.g., April-October), and depths in the mixed layer. In model development research, a mixed-layer depth of 15 ft (4.6 m) was used for data summary purposes; this value should be adjusted in specific applications, based on a review of midsummer temperature profile data. Because the data-summary procedure does not apply weighting factors with depth, use outside of the mixed layer (or in nonhomogeneous depth layers) is not recommended.

The data-summary procedure organizes the data in a two-way table depicting spatial (columns) and temporal (rows) variations. This is illustrated in Figure 3.1 using Beaver Reservoir data. Spatial groups can be defined by station or reservoir segment. Temporal groups are defined by sampling round, which is determined by sample date and date blocking factor specified in the input file. The purpose of date blocking is discussed below. A summary value (mean or median) is computed for each cell (row/column combination). For each row (sampling date), summary values are weighted by surface area and averaged across columns (stations or segments) to compute a reservoir mean concentration. Values are subsequently analyzed vertically to estimate a median, mean, coefficient of variation (CV, standard deviation/mean), and coefficient of variation of the mean (CV(MEAN), standard error/mean).

```
Beaver Reservoir
COMPONENT: total p , DEPTHS:     .0 TO   10.0 M

total p  SAMPLE FREQUENCIES:
SEGMENT        1      4      6      8     10     12 RESERV
DATE  WTS> .050   .100   .150   .250   .250   .200
-----------------------------------------------------------
740405         4      4      3      3      3      3     20
740618         4      4      5      3      4      4     24
740830         4      4      4      3      3      3     21
741009         4      4      4      4      4      4     24
-----------------------------------------------------------
SAMPLES       16     16     16     13     14     14     89
  DATES        4      4      4      4      4      4      4

total p  SUMMARY VALUES:
SEGMENT        1      4      6      8     10     12 RESERV
DATE  WTS> .050   .100   .150   .250   .250   .200
-----------------------------------------------------------
740405      67.0   47.0   37.0   36.0   16.0    9.0   28.4
740618      61.5   89.0   32.0   16.0    9.0    9.5   24.9
740830      49.5   41.5   21.0   15.0   12.0   12.0   18.9
741009      48.0   37.5   21.5   11.0   10.5   10.0   16.8
-----------------------------------------------------------
SAMPLES       16     16     16     13     14     14     89
  DATES        4      4      4      4      4      4      4
 MEDIANS    55.5   44.3   26.8   15.5   11.3    9.8   21.9
   MEANS    56.5   53.8   27.9   19.5   11.9   10.1   22.3
      CV    .164   .443   .284   .575   .254   .130   .241
CV(MEAN)    .082   .222   .142   .287   .127   .065   .121
```

Figure 3.1. Sample PROFILE output: Surface water quality summary

The distinction between the last two statistics (CV and CV(MEAN)) is important. CV is a measure of temporal variability in conditions at a given station (standard deviation expressed as a fraction of the mean). CV(MEAN) is a measure of potential error in the estimate of the MEAN value. From classical sampling theory (Snedecor and Cochran 1979), CV(MEAN) is calculated from the CV divided by the square root of the number of nonmissing rows (sample dates). This assumes that the rows are statistically independent. The calculation of CV(MEANS) for the entire reservoir (last column in Figure 3.1) considers only temporal and random variance components and

assumes that the stations are distributed throughout representative areas of the reservoir.

Estimates of "mean" conditions are generally required for trophic state assessment and empirical modeling (Chapter 4). Direct calculation of arithmetic mean concentrations from all mixed-layer data would be one way of computing desired summary statistics. However, this approach may be undesirable for two reasons:

a. Lack of robustness (a single errant value can have a major impact on the computed mean).

b. Nonrandomness in samples (multiple samples taken within the mixed layer on the same date would tend to be highly correlated).

The PROFILE data summary algorithm has been designed to provide more robust estimates of the mean and coefficient of variation than would be derived from simple averaging.

"Robustness" can be introduced by using medians to compute summary values within each cell. Cells may contain more than one observation as a result of the following:

a. Replicate sampling at a given station, date, and depth.

b. Sampling with depth within the mixed layer (e.g., 0, 2, 4 m).

c. Including more than one station per segment (if segments are used to define columns).

d. Blocking of adjacent sampling dates (specifying date-blocking factors greater than 1 in the input file).

In the Beaver Reservoir example (Figure 3.1), cells contain between two and four observations as a result of sampling with depth. Use of the median in computing a summary value provides some protection against "errant" observations and yields summary statistics (across stations and across dates) that are less sensitive to outliers. For example, a cell containing five observations (10, 20, 15, 12, 100) would be summarized by a mean of 31 and a median of 15. The median is less dramatically influenced by the single high value.

Medians provide "filtering" of outliers only in cells containing at least three observations, which may be achieved by replicate sampling, sampling with depth, including more than one station per reservoir segment, and/or blocking of adjacent dates. Generally, date blocking should not be used unless the sampling frequency is at least biweekly and the resulting number of rows is at least three. In such cases, date blocking may also improve the CV and CV(MEAN) estimates by reducing serial dependence in the rows.

While the calculation procedure accounts for missing values in the two-way table, the usefulness and reliability of the surface water quality summary are enhanced by complete sampling designs (i.e., each station sampled on each date). Based upon review of box plots and two-way tables, monitoring programs can be refined by reducing excessive redundancy across stations, improving characterization of spatial gradients, and modifying temporal sampling frequency to achieve the desired precision in summary statistics.

Figure 3.2 illustrates the use of a Box Plot to summarize spatial variations in mixed-layer total phosphorus concentrations. In generating Box Plots, data can be grouped by station, segment, month, round, year, or depth interval. An accompanying table (not shown) summarizes the distribution of measurements with each data group (percentiles, median, mean, CV).

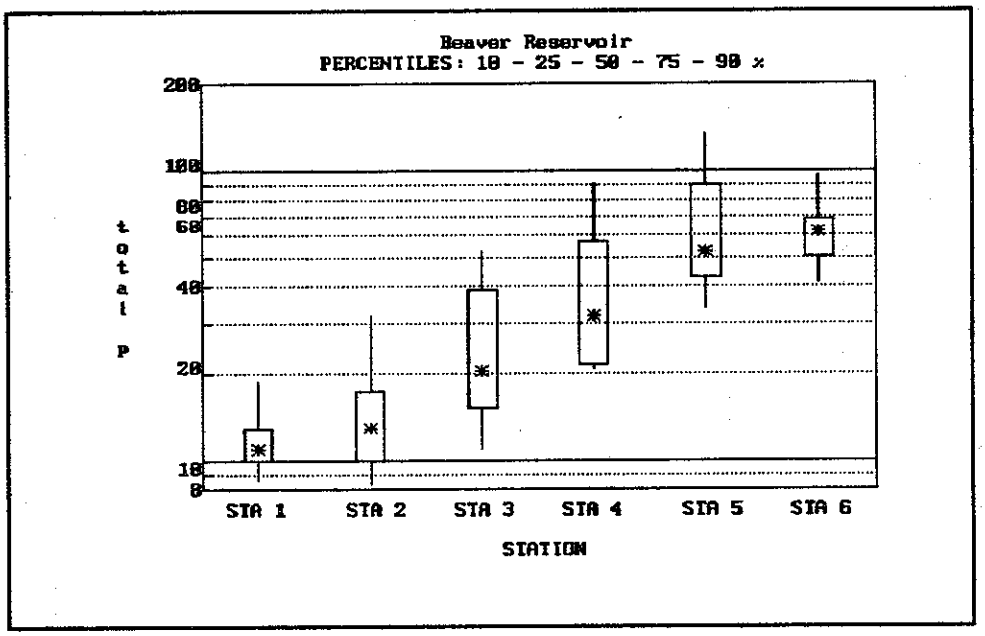


Figure 3.2. Example box plot for Beaver Reservoir

Oxygen Depletion Calculations

This section presents an overview of the procedures for calculating oxygen depletion rates in stratified reservoir using PROFILE. Calculations are illustrated in the Documented Session section of this chapter. Calculations are applied to vertical oxygen profiles at a given station; simultaneous measurements of temperature are also required to characterize thermal stratification. Empirical models have been developed for relating near-dam oxygen depletion rates to surface-layer chlorophyll *a* concentrations (Walker 1985). Accordingly, the procedure would normally be applied to data from near-dam stations.

For the present purposes, the areal hypolimnetic oxygen depletion rate (HODa, mg/m^2-day) is defined as the rate of decrease of dissolved oxygen mass (mg/day) in the reservoir hypolimnion divided by the surface area of the hypolimnion (m^2). The rate is also expressed on a volumetric basis (HODv, mg/m^3-day), which is essentially the rate of decrease of the volume-weighted-average dissolved oxygen concentration in the hypolimnion between two dates, or HODa divided by the mean depth of the hypolimnion (m). These rates are symptoms of eutrophication because they partially reflect the decay of organic loadings resulting from surface algal growth and sedimentation.

The initial oxygen concentration at the onset of stratification (usually on the order of 10 to 12 g/m^3) and HODv determine the days of oxygen supply. Subtracting the days of oxygen supply from the length of the stratified period (typically 120 to 200 days) provides an estimate of the duration of anaerobic conditions. While HODv is of more immediate concern for water quality management purposes, HODa is a more direct measure of surface productivity because it is relatively independent of reservoir morphometric characteristics. For a given surface productivity and HODa, HODv is inversely related to mean hypolimnetic depth. Thus, the morphometry of the reservoir has a major impact on the severity of hypolimnetic oxygen depletion at a given surface water quality condition.

In a given stratified season, the areal and volumetric depletion rates are calculated between two monitored dates, the selection of which is important. The following criteria are suggested for selection of appropriate dates:

a. Reasonable top-to-bottom distribution of oxygen and temperature measurements.

b. Vertically stratified conditions, defined as top-to-bottom temperature difference of at least 4 °C.

c. Mean hypolimnetic oxygen concentrations in excess of 2 g/m^3.

The first criterion provides adequate data for characterizing thermal stratification and volume-weighting (estimation of total oxygen mass and volume-weighted concentration) within the hypolimnion on each sampling date. The second criterion is based upon the concept that HODa is valid as a measure of productivity only in water bodies that have stable vertical stratification. The calculation is meaningless in unstratified or intermittently stratified reservoirs because of oxygen transport into bottom waters. The 4 °C temperature difference is an operational criterion employed in developing data sets for model calibration and testing (Walker 1985). Special consideration must be given to water bodies with density stratification that is not related to temperature. The third criterion is designed to minimize negative biases caused by calculating HODa values under oxygen-limited conditions. The underlying model assumes that the depletion rate is limited by the organic supply, not the oxygen supply.

The first date generally corresponds to the first profile taken after the onset of stratification. The last date corresponds to the last profile taken before the end of August, the loss of stratification, or the loss of hypolimnetic dissolved oxygen (mean $<2g/m^3$), whichever occurs first. Due to existing data limitations, it is sometimes difficult to conform to all of the above criteria in selecting dates. Small deviations may be acceptable, but should be noted and considered in interpreting subsequent modeling results.

To permit calculation of hypolimnetic and metalimnetic depletion rates between two dates, fixed thermocline boundaries (top and bottom) must be specified. Temperature profile displays can assist in the selection of appropriate boundaries. The bottom of the thermocline (metalimnetic/hypolimnetic boundary) is set at the intersection of one line tangent to the region of maximum temperature gradient and another line tangent to the bottom of the profile. The top of the thermocline (epilimnetic/metalimnetic boundary) is set at the intersection of one line tangent to the region of maximum temperature gradient and another line tangent to the top of the profile. If significant thermocline migration has occurred between the two sampling dates, calculations should be based upon the thermocline levels at the last sampling date. A degree of subjective judgment must be exercised in interpreting temperature profiles and setting thermocline boundaries. Program output provides perspective on the sensitivity of the calculated depletion rates to the dates and thermocline boundaries employed.

In response to program prompts, the user specifies temperature and oxygen variables, near-dam station description, elevation increment (meters), first and last sampling rounds, and thermocline boundaries. Profiles are interpolated and integrated at the specified elevation increment from the bottom of the reservoir to the top of the water column. At elevations below the deepest sampling point, concentrations and temperatures are set equal to those measured at the deepest sampling point. Results are most reliable when the profiles are complete and the morphometric table (Input Data Group 3) has been specified in detail.

Procedure output is in the form of several tables and plots that are useful for tracking the calculations and evaluating sensitivity to sampling date and thermocline selections. Interpolated profiles and the summary table for Beaver Reservoir are displayed in the Documented Session section. The summary table can be considered the "bottom line" in the calculations. The Beaver Reservoir example illustrates a pronounced metalimnetic oxygen depletion, which is often found in relatively deep reservoirs.

Program Operation

Introduction

This section describes the PROFILE menu structure and operation procedures. When the program is run (from the DOS prompt), a series of help

screens summarizing model features is first encountered. If error messages appear, it generally means that one of the PROFILE program files has been corrupted or that your computer does not have enough available memory. Try reinstalling the program. Try unloading any memory-resident software. If you are trying to run the program from Windows, try exiting Windows and running directly from DOS. The introductory screens are followed by a menu that provides interactive access to eight types of procedures with the following functions:

```
P R O F I L E - VERSION 4.5
Data    Window    Plot    Calculate    Utilities    Help    Quit

Data          Read or List Data
Window        Set Data Window
Plot          Select Plot Formats
Calculate     Calculate Oxygen Depletion Rates or Mixed-Layer Summaries
Utilities     Program Utilities
Help          Display Help Screens
Quit          End Profile Session
```

A procedure category is selected by moving the cursor (using arrow keys) or by pressing the first letter of the procedure name. Selected procedures in the menu box are highlighted on the screen and underlined in the following documentation. Assistance in navigating around the menu can be obtained by pressing the **<F7>** function key. A **Help** screen describing the selected procedure can be viewed by pressing **<F1>**. After each procedure is completed, control returns to the above menu screen.

Data procedures

Data procedures control input and listing of sample data and other information derived from the input file:

```
P R O F I L E - VERSION 4.5
Data    Window    Plot    Calculate    Utilities    Help    Quit
Read      List      Keys      Inventory

Read          Read Input Data File
List          List Sample Data
Keys          List Morphometric Table, Station Key, Date Key
Inventory     Inventory Data By Component, Station, and Date
```

The **Data/List** lists the sample data in one of two sort sequences:

```
P R O F I L E - VERSION 4.5
Data    Window    Plot    Calculate    Utilities    Help    Quit
Read      List      Keys      Inventory
1 Sort      2 Sort

1 Sort        List Data Sorted by Station, Date, Depth
2 Sort        List Data Sorted by Date, Station, Depth
```

Window procedures

Window procedures are used to select subsets of the data for subsequent calculations and plotting:

```
P R O F I L E - VERSION 4.5
Data      Window     Plot      Calculate     Utilities     Help     Quit
Date/Depth         Components      Stations       All        Reset

Date/Depth      Define Date, Season, & Depth Ranges
Components      Define Water Quality Components
Stations        Define Sampling Stations
All             Define Date, Season, Depth, Station, & Components
Reset           Reset Window to Include All Data
```

Window parameters remain in effect until another data file is read or one of the **Window/Reset** procedures is selected:

```
P R O F I L E - VERSION 4.5
Data      Window     Plot      Calculate     Utilities     Help     Quit
Date/Depth         Components      Stations       All       Reset
Date/Depth         Components      Stations       All

Date/Depth      Reset Window to Include All Dates and Depths
Components      Reset Window to Include All Components
Stations        Reset Window to Include All Stations
All             Reset Window to Include All Dates, Depths, Components, Stati
```

Plot procedures

Plot procedures permit display of water quality data in several formats:

```
P R O F I L E - VERSION 4.5
Data      Window     Plot      Calculate     Utilities     Help     Quit
Line      Contour     General     Histograms     Box-Plots     Options

Line            Use Pre-Defined Line Plot Format
Contour         Use Pre-Defined Contour Plot Format
General         Create a Custom Plot Format
Histograms      Plot Histograms
Box-Plots       Data Summaries & Box Plots by Station, Date, Etc...
Options         Set Graphics Options
```

Plot/Line procedures include eight predefined formats:

```
P R O F I L E - VERSION 4.5
Data      Window     Plot      Calculate     Utilities     Help     Quit
Line      Contour     General     Histograms     Box-Plots     Options
1PR/S/D  2PR/D/S  3PR/D/Y  4C/R/D  5C/D/S  6C/S/SY  7C/D/ZS  8C/D/ZY

1PR/S/D         Vertical Profiles, Symbol = Station, Repeated for Each Date
2PR/D/S         Vertical Profiles, Symbol = Date, Repeated for Each Station
3PR/D/Y         Vertical Profiles, Symbol = Date, Repeated for Each Year
4C/R/D          Concentration vs. RKM, Symbol = Date
5C/D/S          Concentration vs. Date, Symbol = Station
6C/S/SY         Conc. vs. Season, Symbol = Station, Repeated for Each Year
7C/D/ZS         Conc. vs. Date, Symbol = Depth Interval, For Each Station
8C/D/ZY         Conc. vs. Season, Symbol = Depth Interval, For Each Year
```

Plot/Contour procedures include four predefined formats:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
Line     Contour    General     Histograms     Box-Plots     Options
1E/S/S     2E/S/Y     3E/D/S     4E/R/D
```

1E/S/S	Elevation vs. Season Contour Plot, Repeated for Each Station
2E/S/Y	Elevation vs. Season Contour Plot, Repeated for Each Year
3E/D/S	Elevation vs. Date Contour Plot, Repeated for Each Station
4E/R/D	Elevation vs. RKM Contour Plot, Repeated for Each Date

Using the **Plot/General** procedures, the user can create a custom plot format:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
Line     Contour    General     Histograms     Box-Plots     Options
Prompt     Screen
```

Prompt	Create Custom Plot Format - Prompt Method
Screen	Create Custom Plot Format - Screen Method

Plot formats are defined by the water quality component displayed, X-axis variable, Y-axis variable, symbol variable, and repeat variable. A separate plot is generated for each unique value of the repeat variable. Frequency distributions are displayed using the **Plot/Histograms** procedure:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
Line     Contour    General     Histograms     Box-Plots     Options
```

Histograms	Plot Histograms

Plot/Box-Plots includes vertical or horizontal formats:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
Line     Contour    General     Histograms     Box-Plots     Options
Vertical     Horizont
```

Vertical	Vertical Box Plot
Horizont	Horizontal Box Plot

Box plots are accompanied by a table with summary statistics. Use **Plot/Options** to set any of eight options:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
Line     Contour    General     Histograms     Box-Plots     Options
Intervals   LogScale   Scaling   Grouping   Reduction   Break   Contour
```

Intervals	Edit Contour Intervals & Depth Intervals for Plotting
LogScale	Select Variables to Be Plotted on Logarithmic Scales
Scaling	Set Automatic or Manual Plot Scaling
Grouping	Set Scaling Options for Plot Groups
Reduction	Method for Summarizing Multiple Values at Same Plot Location
Break	Set Option to Break Lines at End of Year
Contour	Set Contour Plot Resolution & Format

Calculate procedures

Calculate procedures can be selected to estimate oxygen depletion rates and to generate mixed-layer water quality summaries:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
HOD      Summaries          Options

HOD          Calculate Hypolimnetic Oxygen Depletion Rates
Summaries    Summarize Water Quality Data - Calculate Area-Weighted Means
Options      Set Options for Data Summaries
```

Select **Calculate/Options** to change default settings for options controlling the calculation of mixed-layer summaries:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
HOD      Summaries          Options
Length     Columns           Method

Length       Set Output Format:  Short or Long (default)
Columns      Set Column Option:  Segments (default) or Stations
Method       Set Cell Summary Method: Medians (default) or Means
```

Calculate/Options/Length defines the output format:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
HOD      Summaries          Options
Length     Columns           Method
Long     Short

Long         Long Output Format (Default)
Short        Short Output Format - BATHTUB Inputs Only
```

The **Long** format contains a table of sample frequencies and a table of concentrations for each component. The **Short** format contains only the means and coefficients of variation for each column and for the entire reservoir. **Calculate/Options/Columns** defines the column attribute of the data-summary table:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
HOD      Summaries          Options
Length     Columns           Method
1Segments    2Stations

1Segments    Table Columns = Reservoir Segments (default)
2Stations    Table Columns = Sampling Stations
```

Calculate/Options/Method sets the method used for summarizing multiple observations in a given cell of the data-summary table:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
HOD      Summaries          Options
Length     Columns           Method
1Medians     2Means

1Medians     Use Medians to Summarize Table Cells (default)
2Means       Use Means to Summarize Table Cells
```

Utilities procedures

Utilities procedures can be selected to route output to a disk file or to view any disk file:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
Output      View

Output        Select Output Destination
View          View Any ASCII File
```

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
Output      View
Disk       Screen

Disk          Direct Output To Disk File
Screen        Direct Output to Screen (Default)
```

Help procedures

The **Help** procedure provides access to supplementary help screens, organized in four topics:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit

Help          Display Help Screens

HELP TOPICS
INTRODUCTORY SCREENS
PROCEDURES
PLOTTING
PROGRAM MECHANICS
```

Quit procedure

The **Quit** procedure ends the current session, after asking for verification:

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit

Quit          End Profile Session

QUIT ?
```

Input Data File Format

PROFILE requires a formatted ASCII input data file containing seven groups of data. The specified formats, descriptions, and limitations of each group are given in detail below.

Group 1: **Title** (maximum = 40 characters)
FORMAT(5A8)

Group 2: **Parameters and Conversion Factors**
FORMAT (F8.4)

NOTES:

a. There are seven records (one value per record) in Data Group 2.

b. The values should be entered in the following order:

Reservoir Length (km or Miles)	- record 1
Missing Value Code (Suggest -9)	- record 2
Conversion Factor - Elevations to Meters	- record 3
Conversion Factor - Surface Areas to km^2	- record 4
Conversion Factor - Distance to km	- record 5
Conversion Factor - Sample Depths to Meters	- record 6
Date Blocking Factor, Days (Normally = 1)	- record 7

c. The conversion factors are multiplied by the input units to get the program units (metric).

Area units = SQUARE KILOMETERS (km^2)
Elevation and Depth units = METERS (m)

Group 3: **Reservoir Morphometry** - ELEV, AREA
FORMAT (2F8.0)

ELEV = Surface elevation, in increasing order (maximum = 29 entries)

AREA = Surface Area

NOTES:

a. The first entry must be the bottom of the reservoir (invert, AREA = 0).

b. The units should be consistent with the conversion factors in Data Group 2.

c. Decimal points should be included or right-justified.

d. The last record of Data Group 3 must be - "00".

Group 4: **Component Key** - IC, LABEL, V1, ..., V6
FORMAT (I2,1X,A8,6F5.0)

IC	=	Component sequence number in Data Group 7
LABEL	=	Variable name (e.g., TEMP, OXYGEN, TOTAL P) (maximum = 8 characters)
V	=	Cutpoints to be used to define contour intervals

NOTES:

a. Include the decimal points in V1-V6, or right-justify the entries.

b. The last record of Data Group 4 must be - "00".

c. Cutpoints can be edited from within the program using the Plot/Options/Interval procedure.

Group 5: **Station Key** - ST, CODE, ELEV, RINDEX, WT, SEG, DESC
FORMAT (I2,1X,A8,3F8.0,I4,2A8)

ST	=	Station number used in sample records (must be in ascending order)
CODE	=	User station code (for general reference) (maximum = 8 characters)
ELEV	=	Elevation of reservoir bottom at the station
RINDEX	=	Distance along thalweg from the major inflow (mainstream stations) (used only for plotting purposes, ignored if <0)
WT	=	Factors used in area-weighted averaging across stations (relative surface area represented by station (estimated from maps) - weights are rescaled by the program and do not have to sum to 1.0)
SEG	=	Integer segment number, used for grouping stations by the reservoir area
DSC	=	Station location description (maximum = 16 characters)

NOTES:

a. Include one record for each station in Data Group 7 (maximum = 50)

b. Include the decimal point in ELEV, RINDEX, WEIGHT, or right-justify the entries.

c. Input units must be consistent with the conversion factors specified in Data Group 2.

d. The last record of Data Group 5 must be - "00".

Group 6: **Elevation Key** - DATE, SELEV
FORMAT (3I2,F10.0)

DATE	=	Sample date in YYMMDD format (e.g., 840126)
SELEV	=	Surface elevation of the reservoir at the dam on the sample date

NOTES:

a. Include one record for each sample date in Date Group 7.

b. Dates must be in chronological order (maximum = 100 dates).

c. Input units must be consistent with the conversion factors specified in Data Group 2.

d. Group must contain at least two records; if an elevation record is not specified for a given sample date, it is estimated by interpolation from adjacent elevation records.

e. The last record of Data Group 6 must be - "00".

Group 7: **Profile Data** - ST, DATE, DEPTH, C1, ..., C10
FORMAT (I2,1X,3I2,11F5.0)

ST	=	Station number, indexed in Data Group 5
DATE	=	Sample date in YYMMDD format, indexed in Data Group 6
DEPTH	=	Sample depth
C	=	Component concentrations, indexed in Data Group 4 (IC value) (maximum = 10)

NOTES:

a. Records may be in any order.

b. Include the decimal point in DEPTH and C1-C10, or right-justify the entries.

c. Input units must be consistent with the conversion factors specified in Data Group 2.

d. The last record of Data Group 7 must be - "00".

Note: Inclusion of data in Group 7 is optional. The file name(s) of spreadsheet or free-format ASCII data files containing sample data may be substituted. Any number of file names may be specified (one per line). The component labels in Group 4 should correspond with the field labels in the data files (not necessarily a 1-to-1 correspondence). PROFILE will read data from any components contained in both Group 4 and the data file. Station codes in the data files should correspond to the Station codes (8-character alphanumeric) specified in Group 5. The following file formats are supported:

*.WK1 - Lotus-123 worksheet

*.ASC - ASCII

File formats and conventions are described in Chapter 2 (FLUX - Data File Formats).

A sample input data file, BEAVER.PRF, is listed below:

```
Beaver Reservoir - EPA/NES Data
120.                        *** length   (kilometers)
-9.                         *** missing value code
.305                        *** elevation conversion to m
.00405                      *** area conversion to km2
1.0                         *** rkm conversion to km
.305                        *** depth unit conversion factor to m
1.                          *** date fuzz factor
elev--->area--->            ** hypsiographic curve in increasing order ft, acres
 914.        0.
 938.      240.
 982.     1830.
1050.     9750.
1077.    15540.
1080.    16210.
1090.    18800.
1093.    19690.
1100.    21830.
1110.    24950.
1120.    28220.
1130.    31700.
1137.    35860.
1142.    36260.
00
ic label   <--><--><--><--><--><-->                  *** component key
01 temp     8.   12.  16.  20.  24.  28.
02 oxygen   2.   4.   6.   8.   10.  12.
03 total p  20.  40.  80.  160. 320.
00
st code--->elev--->rkm---->weight-> seg description---->  *** station key
01 STA 1       916.   119.0     .20  12 above dam
02 STA 2       951.   100.0     .25  10 big city
03 STA 3       999.    76.0     .25  08 below rogers
04 STA 4      1018.    51.8     .15  06 above rogers
05 STA 5      1054.    32.0     .10  04 below war eagle
06 STA 6      1073.     5.7     .05  01 headwater
```

```
00
date--selev--->                                          *** elevation key
740405   1124.
740618   1124.
740830   1118.
741009   1119.
00
st date-- depth temp   o2 ptot                           *** sample records
01 740405    0            9.
01 740405    5 11.6 10.0  9.
01 740405   15 11.6 10.0 16.
01 740405   50 11.5 10.0 10.
etc.
00
```

NOTE: Spreadsheet file names for free-format ASCII file names may be substituted for sample records. See example file 'BEAVER2.PRF'.

Data-Entry Screens

DATA-ENTRY SCREEN: Data/Read

```
                PROFILE DATA INPUT SCREEN

CASE TITLE:        ________________________________

PATH:              ________________________________

DATA FILE:         ________________________________

SAMPLE DATE RANGE:  ______ TO ______   <YYMMDD>

SEASON RANGE:       ____ TO ____       <MMDD>

DEPTH RANGE:        ______ TO ______   <METERS>
```

HELP SCREEN:

```
Data Read

Reads Input Data File.

If FILE NAME is blank, user selects from list of all Profile data
   sets in PATH (Default File Extension = *.PRF)

Can define date, season, depth ranges to be read.

Set limits to 0,0 to read all data.

Up to 10 variables can be read.
```

DATA-ENTRY SCREEN: Window/Date/Depth

```
                PROFILE  DATA  WINDOW

SAMPLE DATE RANGE:   ______ TO ______   <YYMMDD>

SEASON RANGE:        _____ TO _____     <MMDD>

DEPTH RANGE:         ______ TO ______   <METERS>
```

HELP SCREEN:

```
Data Window Date/Depth

Defines Date, Season, Depth Ranges for Data to Be Used in
Plotting, Listing, Summary Procedures.

Limits are Inclusive, e.g.,    MIN <=  value <=MAX.

Limits of (0,0) or (MIN=MAX) will include all samples.

Season Limits Wrap Around Calendar, e.g.,
   MIN=0401,  MAX=0930 :  Samples between April 1 and Sept 30
   MIN=0930,  MAX=0401 :  Samples between Sept 30 and April 1
```

DATA-ENTRY SCREEN: Plot/Options/Intervals

```
          EDIT VARIABLE AND DEPTH CUTPOINTS
       Upper Limit ( < = ) of Contour Interval

    VARIABLE      1     2     3     4     5     6
 1  _______     ____  ____  ____  ____  ____  ____
 2  _______     ____  ____  ____  ____  ____  ____
 3  _______     ____  ____  ____  ____  ____  ____
 4  _______     ____  ____  ____  ____  ____  ____
 5  _______     ____  ____  ____  ____  ____  ____
 6  _______     ____  ____  ____  ____  ____  ____
 7  _______     ____  ____  ____  ____  ____  ____
 8  _______     ____  ____  ____  ____  ____  ____
 9  _______     ____  ____  ____  ____  ____  ____
10  _______     ____  ____  ____  ____  ____  ____

    DEPTH (M)   ____  ____  ____  ____  ____  ____

   Values Must be In Increasing Order, 0 = Missing
```

HELP SCREEN:

```
Plot Options Intervals

Edit Contour Intervals for each variable.
Edit Depth Intervals used to group data in line plots.
Each Entry Defines the Upper Limit (<=) of an Interval.
Entries Must Be in Increasing Order.

A '0' Signals End of List, So Cutpoints of 0 Are Illegal.

VALID  : 2  4  6  8  10  0    < 5 intervals (trailing 0 ignored)
VALID  : 2  4  0  0   0  0    < 2 intervals
INVALID: 2  6  4  0   0  0    < wrong order
INVALID: 0  2  4  6           < 0 intervals (leading 0 invalid)
VALID  : 2  4  6  8  10 12    < 6 intervals

Last Row Defines Depth Ranges for Plots using Depth Intervals.
```

DATA-ENTRY SCREEN: Plot/General/Screen

```
        PLOT TITLE: ______________________________

  1-_______  2-_______  3-_______  4-_______  5-_______
  6-_______  7-_______  8-_______  9-_______  10_______

COMPONENT NUMBERS PLOTTED: ___  ___  ___   <---all on same plot

X-AXIS: ___   1=DATE  2=SEASON  3=JULIAN  4=RKM  5=CONC 6=LOG(C)
              7=YEAR  8=MONTH   9=YR-MONTH

Y-AXIS: ___   0=NONE 1=ELEV 2=CONC 3=LOG(CONC) 4=-DEPTH

SYMBOL VARIABLE: ___   0=NONE  1=STATION 2=SEGMENT 3=DATE 4=YEAR
                       5=DEPTH INTERVAL 6=CONC INTERVAL (CONTOUR

REPEAT VARIABLE: ___   0=NONE  1=STATION  2=SEGMENT  3=DATE 4=YR

SUMMARY METHOD : ___   0=NONE  1=MEANS  2=MEDIANS
```

HELP SCREEN:

```
Plot General Screen

Fill in Table As Indicated - Choices Shown on Right.

At Least One Component and X-Axis Must Be Specified.

To Specify Histogram, Set X-Axis to CONC or LOG(C) and
Set Y-Axis to NONE.

If More Than One Component is Specified, All Will Appear
on Same Plot and SYMBOL Choice Will be Ignored.

Press <ESC> to Return to Main Menu
```

Documented Session

The PROFILE documented session uses the BEAVER.PRF file (found on the distribution diskette and copied to the hard drive during installation) as the input data set. This file contains data for Beaver Reservoir in Arkansas for the growing season of 1974, and these data were taken as part of the National Eutrophication Survey. The documented session illustrates the screens as they would appear as the program is run. Notes to the user are in italics below. Selected menu items are underlined. To begin, enter 'profile' at the prompt.

>PROFILE

```
                    P R O F I L E

                RESERVOIR DATA ANALYSIS

                    VERSION 4.5

                Environmental Laboratory
            USAE Waterways Experiment Station
                 Vicksburg, Mississippi

                    March 1995

PRESS KEY TO CONTINUE, <ESC> RETURN TO MENU                100
```

A series of introductory screens appear. These contain brief descriptions of the program and summarize any new features not documented in this manual. To bypass these screens, press <Esc> *and the program menu will appear.*

```
                    P R O F I L E - VERSION 4.5
Data      Window      Plot      Calculate    Utilities   Help  Quit
Read      List       Keys      Inventory


     Read or List Data

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP

CASE       =
DATA FILE  =
            WINDOW  TOTAL
STATIONS   =   0      0        PLOT OPTIONS:
DATES      =   0      0        SCALING    =  AUTOMATI MANUAL
COMPONENTS =   0      0        GROUPING   =  SEPARATE GROUPED
RECORDS    =   0      0        REDUCTION  =  POINTS   MEANS    MEDIANS
                                LINE BREAK =  NO       YES
OUTPUT FILE = SCREEN
```

A one-line message describing the currently selected procedure appears at the bottom of the menu box. Characteristics of the current data set and program option settings are listed on the bottom half of the screen. Since no data set has been loaded, the above values are zeroes or blank.

Select **Data/Read** *to read in a data set for Beaver Reservoir:*

```
                    PROFILE DATA INPUT SCREEN

CASE TITLE:        Beaver Reservoir

PATH:

DATA FILE:         beaver.prf

SAMPLE DATE RANGE:   0      TO 0        <YYMMDD>

SEASON RANGE:        0      TO 0         <MMDD>

DEPTH RANGE:         0      TO 0        <METERS>

          case title
F1=HELP,  F2=DONE/SAVE,  F3=EDIT FIELD,  F7=HELP/EDITOR,  <ESC>=ABORT
```

This screens the data file and data ranges to be selected. Hit **<F2>** *after editing and the file is read:*

```
OPENING INPUT FILE: beaver.prf
Beaver Reservoir - EPA/NES Data
READING MORPHOMETRY...
READING COMPONENT KEY...
READING STATION KEY...
   6 STATIONS    0 SAMPLES    0 DATES  3 COMPONENTS LOADED

SELECT STATIONS

                          STATIONS
                        * above dam
                        * big city
                        * below rogers
                        * above rogers
                        * below war eagle
                        * headwater

     PRESS <SPACE> TO SELECT(*) OR NO( ), <ENTER>=DONE, <a>= ALL, <n>=NONE
```

Select the stations to be used in this window. All are selected (*) in this example.

```
OPENING INPUT FILE: beaver.prf
Beaver Reservoir - EPA/NES Data
READING MORPHOMETRY...
READING COMPONENT KEY...
READING STATION KEY...
   6 STATIONS    0 SAMPLES    0 DATES  3 COMPONENTS LOADED
PERCENT OF PROGRAM CAPACITY =      .0%
STATIONS SELECTED =          6/          6

SELECT VARIABLES

                          VARIABLE
                        * temp
                        * oxygen
                        * total p

     PRESS <SPACE> TO SELECT(*) OR NO( ), <ENTER>=DONE, <a>= ALL, <n>=NONE
```

Select the variables to be used from the above list of all variables contained in the data file. Hit **<Enter>** *to continue.*

```
OPENING INPUT FILE: beaver.prf
Beaver Reservoir - EPA/NES Data
READING MORPHOMETRY...
READING COMPONENT KEY...
READING STATION KEY...
   6 STATIONS    0 SAMPLES    0 DATES  3 COMPONENTS LOADED
PERCENT OF PROGRAM CAPACITY =      .0%
STATIONS SELECTED =          6/          6
COMPONENTS SELECTED =          3/          3
OPENING INPUT FILE: beaver.prf
Beaver Reservoir - EPA/NES Data
READING MORPHOMETRY...
READING COMPONENT KEY...
READING STATION KEY...
READING DATE KEY...
READING PROFILE DATA...
DEVELOPING SAMPLE INDEX...
   6 STATIONS  169 SAMPLES    4 DATES  3 COMPONENTS LOADED
PERCENT OF PROGRAM CAPACITY =     4.2%
<H>
```

The data file has been successfully loaded. Hit **<Enter>** *in response to the <H> prompt to return to program menu.*

```
P R O F I L E - VERSION 4.5
Data      Window     Plot     Calculate     Utilities  Help  Quit
Read      List       Keys     Inventory

     Read or List Data

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP

CASE        = Beaver Reservoir
DATA FILE   = beaver.prf
              WINDOW  TOTAL
STATIONS    =    6      6        PLOT OPTIONS:
DATES       =    4      4        SCALING    =  AUTOMATI MANUAL
COMPONENTS  =    3      3        GROUPING   =  SEPARATE GROUPED
RECORDS     =  169    169        REDUCTION  =  POINTS   MEANS    MEDIANS
                                  LINE BREAK =  NO       YES
OUTPUT FILE = SCREEN
```

Case data can be listed using the **Data/List/1Sort** *procedure:*

```
P R O F I L E - VERSION 4.5
Data      Window     Plot     Calculate     Utilities  Help  Quit
Read      List       Keys     Inventory
1 Sort      2 Sort

     List Data Sorted by Station, Date, Depth

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP

Beaver Reservoir
ST CODE      DATE     DEPTH     temp  oxygen total p
 1 STA 1   740405      .0                      9.0
 1 STA 1   740405     1.5      11.6    10.0    9.0
 1 STA 1   740405     4.6      11.6    10.0   16.0
```

```
  1 STA 1   740405    15.3      11.5    10.0    10.0
  1 STA 1   740405    30.5       8.4     9.6    11.0
  1 STA 1   740405    45.8       7.5     8.8    12.0
  1 STA 1   740405    61.0       7.3     8.4   100.0
  1 STA 1   740618      .0                      10.0
  1 STA 1   740618     1.5      24.4     9.0     9.0
  1 STA 1   740618     4.6      24.2     9.0     8.0
  1 STA 1   740618     7.6      21.9     7.8    13.0
  1 STA 1   740618    12.2      20.4     5.8     9.0
  1 STA 1   740618    16.8      16.5     6.4     7.0
  1 STA 1   740618    27.5      12.6     7.8    10.0
  1 STA 1   740618    39.7      10.8     7.6    12.0
  1 STA 1   740618    52.2       8.5     5.4    22.0
  1 STA 1   740830      .0      26.3     7.6    14.0
  1 STA 1   740830     3.1      26.3     7.5    12.0
  1 STA 1   740830     6.1      26.3     7.8    12.0
  1 STA 1   740830    11.6      20.4      .4    12.0
  1 STA 1   740830    18.3      17.6     1.0    11.0

USE KEYPAD, <F1>=HELP, <F8>=SAVE, <ESC>=QUIT  OUTPUT
```

The **Data/List/2Sort** *procedure generates similar output, but sorted in a different order. The* **Data/Keys** *procedure lists the station, variable, sampling date keys:*

```
                    P R O F I L E - VERSION 4.5
 Data      Window      Plot      Calculate   Utilities  Help     Quit
 Read      List       Keys      Inventory


     List Morphometric Table, Station Key, Date Key

  MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
STA CODE    ELEVATION      RKM  WEIGHT SEGMENT DESCRIPTION
  1 STA 1       279.4    119.0    .200    12   above dam
  2 STA 2       290.1    100.0    .250    10   big city
  3 STA 3       304.7     76.0    .250     8   below rogers
  4 STA 4       310.5     51.8    .150     6   above rogers
  5 STA 5       321.5     32.0    .100     4   below war eagle
  6 STA 6       327.3      5.7    .050     1   headwater

          MAXIMUM CONCENTRATION
LEVEL      temp      oxygen   total p
   1        8.0       2.0     20.0
   2       12.0       4.0     40.0
   3       16.0       6.0     80.0
   4       20.0       8.0    160.0
   5       24.0      10.0    320.0
   6       28.0      12.0       .0

ROUND    DATE  JULIAN SURFACE ELEVATION
   1   740405      95           342.8
   2   740618     169           342.8
   3   740830     242           341.0
   4   741009     282           341.3
<EOF>
```

The **Data/Inventory** *procedure lists the number of concentration values by station and date for each component:*

```
P R O F I L E - VERSION 4.5
Data        Window      Plot       Calculate   Utilities  Help     Quit
Read        List        Keys       Inventory

     List Data Inventory

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
DATA INVENTORY FOR COMPONENT:  1 temp     STATION: 1 above dam
ROUND  DATE   JULIAN  SELEV  SAMPLES   ZMIN   ZMAX   CMIN   CMAX
                       M               M      M      -      -
   1  740405    95   342.8        6    1.5   61.0    7.3   11.6
   2  740618   169   342.8        8    1.5   52.2    8.5   24.4
   3  740830   242   341.0        9     .0   51.9    9.2   26.3
   4  741009   282   341.3       10     .0   53.4    9.5   19.6

DATA INVENTORY FOR COMPONENT:  1 temp     STATION: 2 big city
ROUND  DATE   JULIAN  SELEV  SAMPLES   ZMIN   ZMAX   CMIN   CMAX
                       M               M      M      -      -
   1  740405    95   342.8        5    1.5   48.8    7.2   10.5
   2  740618   169   342.8        9    1.5   49.1    8.7   24.6
   3  740830   242   341.0        8     .0   45.8    9.9   25.9
   4  741009   282   341.3        9     .0   46.4   10.7   19.6

DATA INVENTORY FOR COMPONENT:  1 temp     STATION: 3 below rogers
ROUND  DATE   JULIAN  SELEV  SAMPLES   ZMIN   ZMAX   CMIN   CMAX
                       M               M      M      -      -
   1  740405    95   342.8        5    1.5   35.1    7.3   10.7
   2  740618   169   342.8        7    1.5   36.9    9.7   25.0
   3  740830   242   341.0        6     .0   33.5   11.3   26.1
   4  741009   282   341.3        8     .0   25.6   16.0   19.7

USE KEYPAD, <F1>=HELP, <F8>=SAVE, <ESC>=QUIT  OUTPUT
```

The **Data/Window** *procedures are used to restrict subsequent analyses (***Plot or Calculate***) to certain data ranges.*

```
P R O F I L E - VERSION 4.5
Data     Window     Plot       Calculate      Utilities   Help    Quit
Date/Depth        Components      Stations       All       Reset

     Define Date, Season, & Depth Ranges

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
                PROFILE  DATA  WINDOW

 SAMPLE DATE RANGE:   740405 TO 741009   <YYMMDD>

 SEASON RANGE:        0      TO 0        <MMDD>

 DEPTH RANGE:         0      TO 61       <METERS>
```

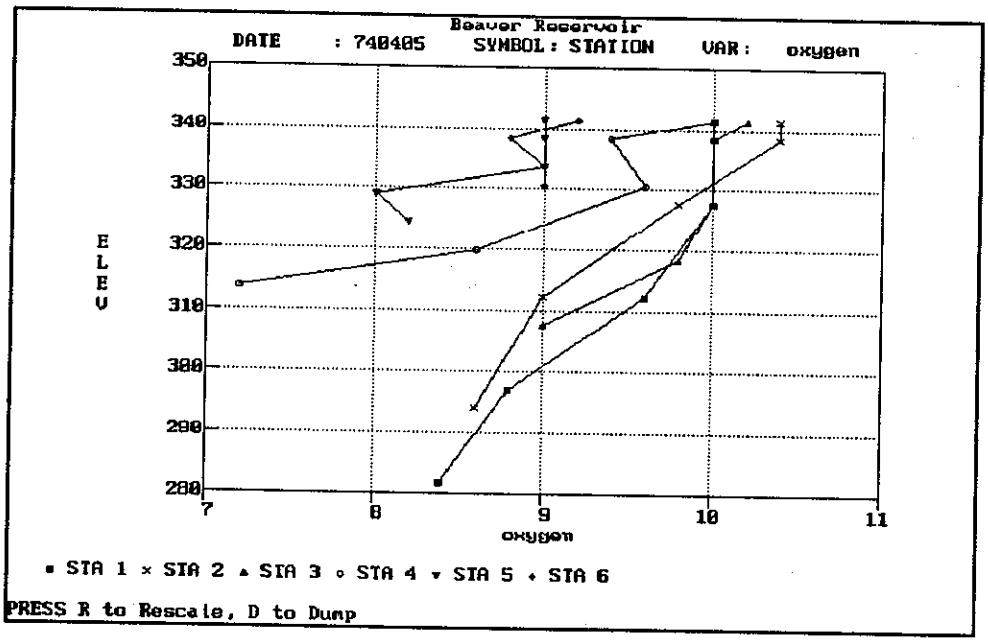
Window parameters are initially set to include the entire range of values in the data set. If the minimum and maximum values are equal, all values are selected. Following are demonstrations of various plot procedures.

```
P R O F I L E - VERSION 4.5
Data        Window      Plot        Calculate     Utilities     Quit
Line        Contour     General     Histograms    Box-Plots     Options
1PR/S/D  2PR/D/S  3PR/D/Y  4C/R/D  5C/D/S  6C/S/SY  7C/D/ZS  8C/D/ZY

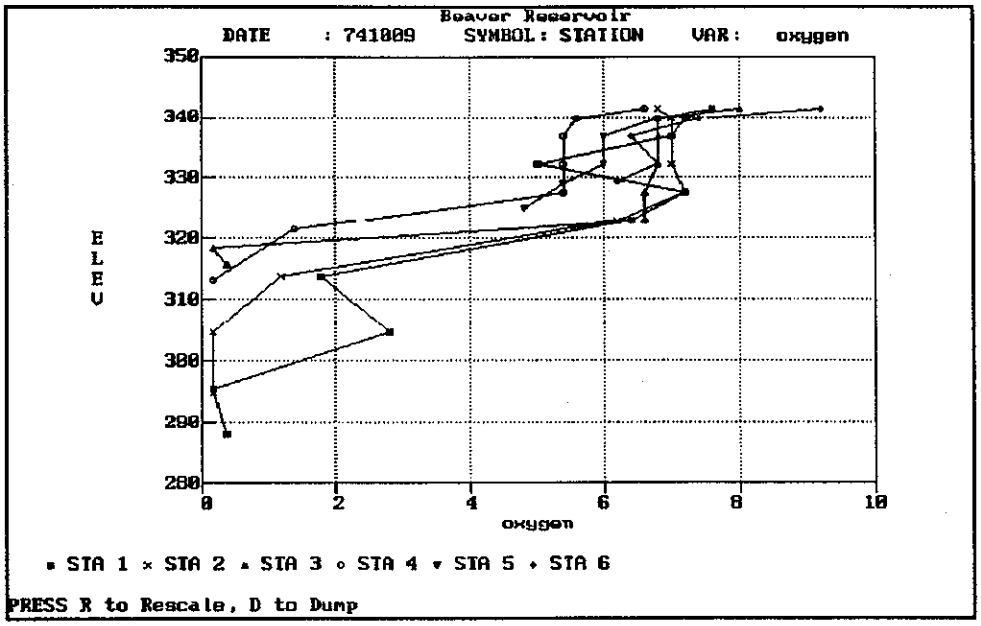
     Vertical Profiles, Symbol = Station, Repeated for Each Date

MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
VARIABLE
  temp
* oxygen
  total p
```



Select the water quality component(s) to be plotted (oxygen). **Plot/Line/1** *generates vertical profiles using different symbols to identify stations. A separate plot is produced for each sampling date.*

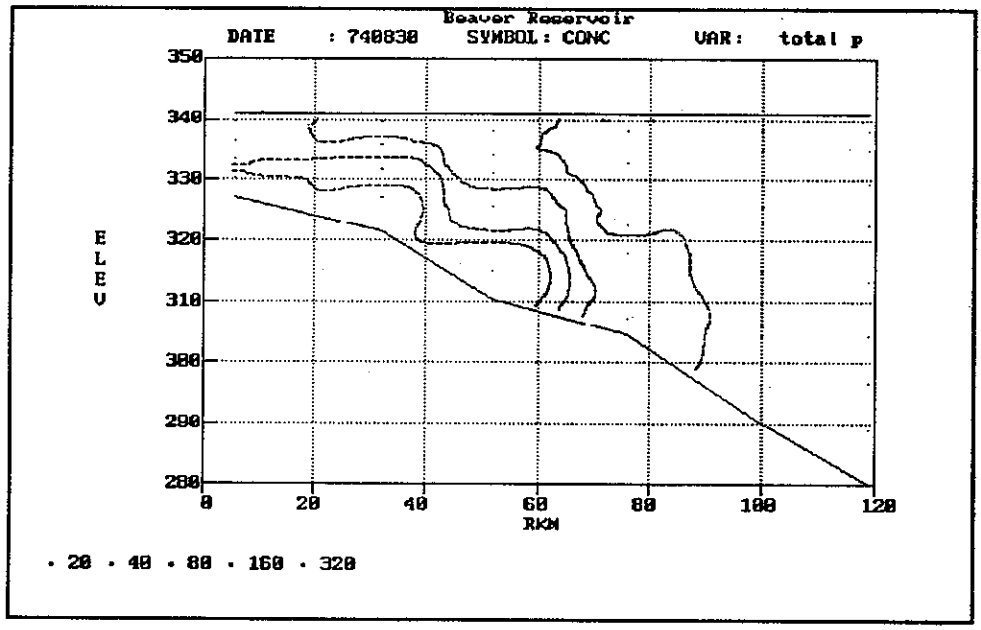


Select **Plot/Contour/4** *to display a longitudinal profile (y = elevation, x = distance along thalweg (i.e., old river channel)). This format only makes sense when all selected stations are in the same tributary arm.*

```
P R O F I L E - VERSION 4.5
Data     Window    Plot      Calculate      Utilities   Help     Quit
Line     Contour   General   Histograms   Box-Plots     Options
1E/S/S      2E/S/Y      3E/D/S      4E/R/D

     Elevation vs. RKM Contour Plot, Repeated for Each Date

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```



Different colors are used to represent contour intervals (not discernable here).

Select **Plot/General** *to define your own plot format. Remember that all plots use data in the current window.*

```
                    P R O F I L E - VERSION 4.5
Data     Window     Plot       Calculate      Utilities   Help     Quit
Line     Contour    General     Histograms    Box-Plots     Options
Prompt     Screen

    Create Your Own Plot Format - Screen Method

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
        PLOT TITLE: Beaver Reservoir

   1-temp      2-oxygen    3-total p   4-          5-
   6-          7-          8-          9-          10

 COMPONENT NUMBERS PLOTTED:   3    0    0  <---all on same plot

 X-AXIS:   4  1=DATE  2=SEASON  3=JULIAN  4=RKM  5=CONC 6=LOG(C)
                      7=YEAR  8=MONTH   9=YR-MONTH

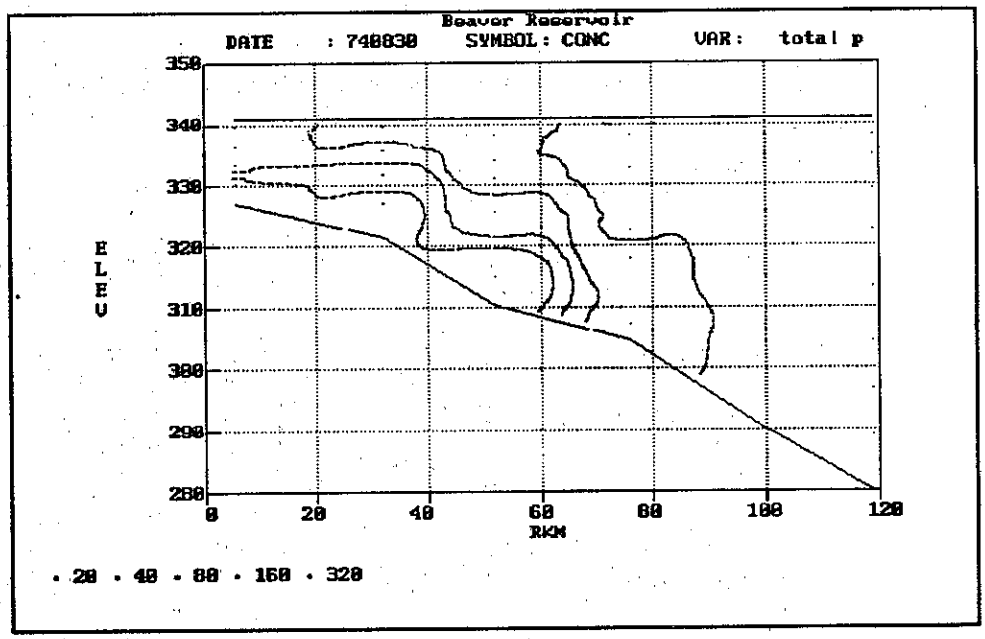
 Y-AXIS:   1  0=NONE 1=ELEV 2=CONC 3=LOG(CONC) 4=-DEPTH

 SYMBOL VARIABLE:   6  0=NONE  1=STATION 2=SEGMENT 3=DATE 4=YEAR
                       5=DEPTH INTERVAL 6=CONC INTERVAL (CONTOUR)

 REPEAT VARIABLE:   3  0=NONE  1=STATION  2=SEGMENT  3=DATE 4=YR

 SUMMARY METHOD :   0  0=NONE  1=MEANS  2=MEDIANS
```

This screen provides a high degree of flexibility for defining plots. In this example, a phosphorus contour plot (elevation versus rkm) is specified. The plot is repeated for each sampling date (only one is shown below).

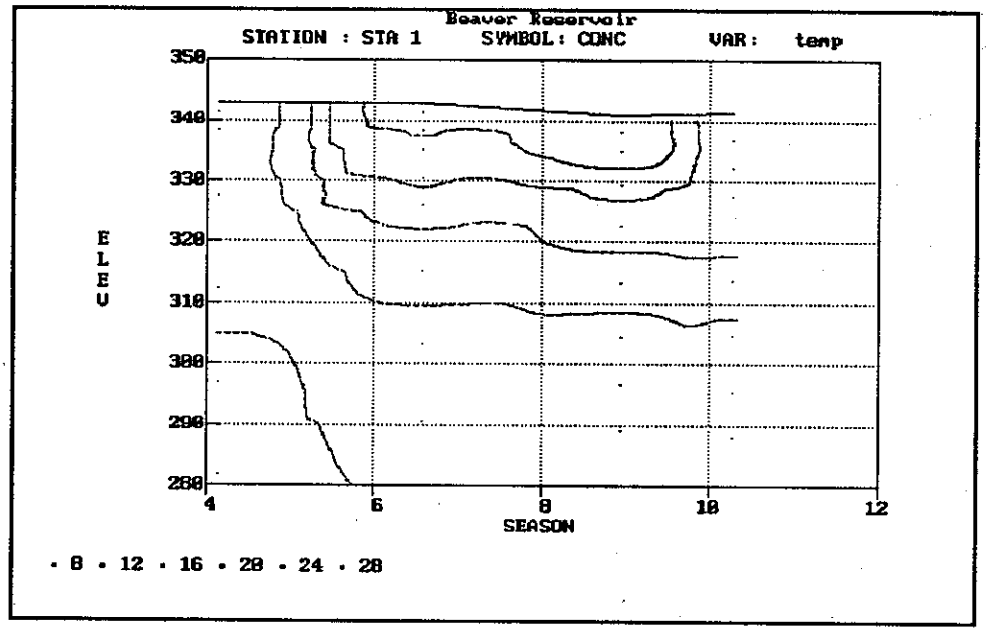


Select **Plot/Contour/1** *to display an elevation versus season (month) contour plot.*

```
P R O F I L E - VERSION 4.5
Data      Window    Plot      Calculate   Utilities   Help      Quit
Line      Contour   General   Histograms  Box-Plots   Options
1E/S/S    2E/S/Y    3E/D/S    4E/R/D

Elevation vs. Season Contour Plot, Repeated for Each Station

MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```



Plot contour intervals can be set using the **Plot/Options/Intervals** *procedure.*

```
P R O F I L E - VERSION 4.5
Data      Window     Plot      Calculate    Utilities    Help     Quit
Line      Contour    General   Histograms   Box-Plots    Options
Intervals  LogScale  Scaling   Grouping     Reduction    Break    Contour

     Edit Component & Depth Intervals for Plotting

MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

EDIT VARIABLE AND DEPTH CUTPOINTS
Upper Limit (< =) of Contour Interval

	VARIABLE	1	2	3	4	5	6
1	temp	8	12	16	20	24	28
2	oxygen	2	4	6	8	10	12
3	total p	20	40	80	160	320	0
4		0	0	0	0	0	0
5		0	0	0	0	0	0
6		0	0	0	0	0	0
7		0	0	0	0	0	0
8		0	0	0	0	0	0
9		0	0	0	0	0	0
10		0	0	0	0	0	0
	DEPTH (M)	6	8	10	18	0	0

Values Must be In Increasing Order, 0 = Missing

F1=HELP, F2=DONE/SAVE, F3=EDIT FIELD, F7=HELP/EDITOR, <ESC>=ABORT

Select **Plot/Options/LogScale** *to define variables to be plotted on log scales (often appropriate for nutrient and chlorophyll data, not appropriate for oxygen or temperature).*

```
P R O F I L E - VERSION 4.5
Data     Window     Plot       Calculate      Utilities    Help    Quit
Line     Contour    General    Histograms     Box-Plots       Options
Interval LogScale   Scaling    Grouping   Reduction   Break    Contour

     Select Variables to Be Plotted on Logarithmic Scales

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

SELECT(*) VARIABLES TO BE PLOTTED ON LOG SCALES

```
  VARIABLE
  temp
  oxygen
* total p
```

Select **Plot/Box-Plots** *to display data summaries by defined groupings.*

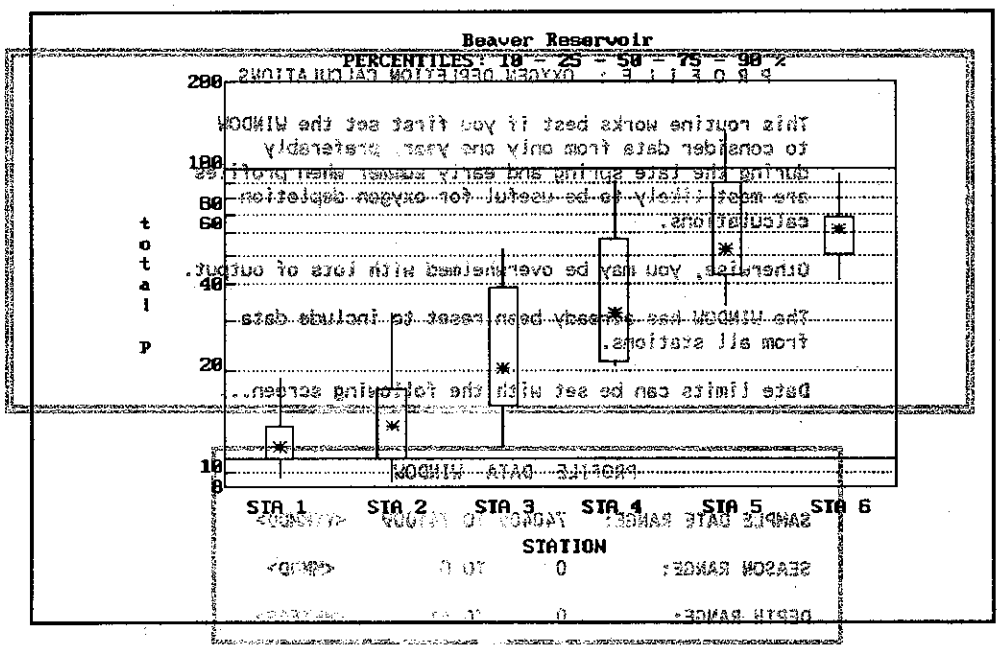
```
P R O F I L E - VERSION 4.5
Data       Window     Plot      Calculate      Utilities   Help     Quit
Line     Contour     General     Histograms     Box-Plots   Options
Vertical       Horizont

     Vertical Box Plot

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

DEFINE GROUPING VARIABLE

```
  CATEGORY
> STATION
  SEGMENT
  DATE
  YEAR
  MONTH
  CONC-I
  DEPTH-I
  NONE
```



ONE-WAY DATA SUMMARY FOR: 3 total p GROUPED BY: STATION
DATE RANGE: 740405 741009 SEASON RANGE: 0 0 DEPTH RANGE: 0 61.0

STATION	N	MIN	10%	25%	50%	75%	90%	MAX	MEAN	CV	CV(M)
STA 1	35	7.0	8.6	10.0	11.0	13.0	19.0	100.0	14.4	1.068	.180
STA 2	33	4.0	8.4	10.0	13.0	17.5	31.8	65.0	16.3	.773	.134
STA 3	28	11.0	11.0	15.3	20.5	39.0	53.0	136.0	30.5	.821	.155
STA 4	29	20.0	21.0	21.5	32.0	57.0	91.0	212.0	50.1	.981	.182
STA 5	23	29.0	33.8	43.0	53.0	90.0	134.6	182.0	70.3	.562	.117
STA 6	20	39.0	41.3	50.5	62.0	68.8	96.2	180.0	67.2	.449	.100

<EOF>

The asterisks (*) show the median value in each data group. The boxes show the 25- to 75-percent range. The lines show the 10- to 90-percent range.

Select **Calculate/HOD** *to calculate areal hypolimnetic depletion rates. This is applicable only to stratified reservoirs and to data sets containing late spring/ early summer oxygen and temperature profiles from a near-dam station.*

```
P R O F I L E - VERSION 4.5
Data     Window     Plot     Calculate     Utilities     Help     Quit
HOD      Summaries          Options

     Calculate Hypolimnetic Oxygen Depletion Rates
```

```
P R O F I L E :  OXYGEN DEPLETION CALCULATIONS

This routine works best if you first set the WINDOW
to consider data from only one year, preferably
during the late spring and early summer when profiles
are most likely to be useful for oxygen depletion
calculations.

Otherwise, you may be overwhelmed with lots of output.

The WINDOW has already been reset to include data
from all stations.

Date limits can be set with the following screen...
```

```
                PROFILE  DATA  WINDOW

SAMPLE DATE RANGE:   740405 TO 741009   <YYMMDD>

SEASON RANGE:        0      TO 0        <MMDD>

DEPTH RANGE:         0      TO 61       <METERS>

 first sample date  >= yymmdd
F1=HELP,  F2=DONE/SAVE,  F3=EDIT FIELD,  F7=HELP/EDITOR,  <ESC>=ABORT
```

As indicated in the above help screen, select the sample date and depth ranges containing the profiles to be used in oxygen depletion calculations. Next, define the temperature variable, oxygen variables, and station:

```
HYPOLIMNETIC OXYGEN DEPLETION (HOD) CALCULATIONS FOR NEAR-DAM STATIONS
SELECT TEMPERATURE VARIABLE

                    VARIABLE
                  > temp
                    oxygen
                    total p
```

```
HYPOLIMNETIC OXYGEN DEPLETION (HOD) CALCULATIONS FOR NEAR-DAM STATIONS
SELECT DISSOLVED OXYGEN VARIABLE

                    VARIABLE
                    temp
                  > oxygen
                    total p
```

```
HYPOLIMNETIC OXYGEN DEPLETION (HOD) CALCULATIONS FOR NEAR-DAM STATIONS
SELECT STATION FOR HOD CALCS

                  STATION
                > above dam
                  big city
                  below rogers
                  above rogers
                  below war eagle
                  headwater
```

Calculations begin. Hit **<Enter>** *to select the default depth interval for the calculations:*

```
TOTAL ELEVATION RANGE =     278.8    342.8  METERS
NOMINAL ELEVATION INCREMENT =     3.20 METERS
ELEVATION INCREMENT ?   3.2

DATA INVENTORY FOR COMPONENT:  1 temp     STATION: 1 above dam
ROUND  DATE   JULIAN  SELEV  SAMPLES   ZMIN   ZMAX   CMIN   CMAX
                       M               M      M      -      -
   1  740405    95   342.8       6    1.5   61.0    7.3   11.6
   2  740618   169   342.8       8    1.5   52.2    8.5   24.4
   3  740830   242   341.0       9     .0   51.9    9.2   26.3
   4  741009   282   341.3      10     .0   53.4    9.5   19.6

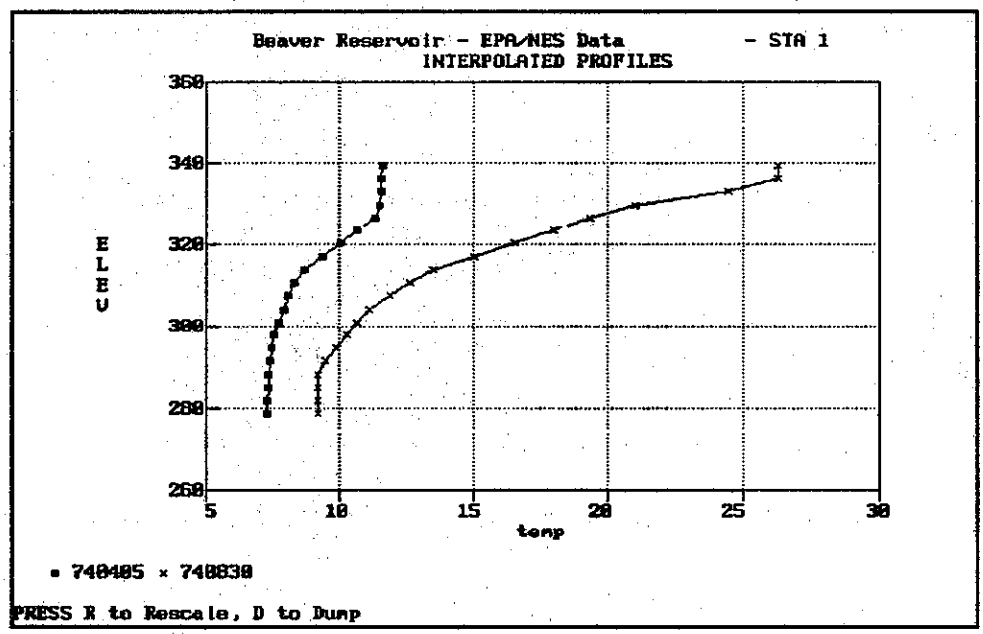
DATA INVENTORY FOR COMPONENT:  2 oxygen   STATION: 1 above dam
ROUND  DATE   JULIAN  SELEV  SAMPLES   ZMIN   ZMAX   CMIN   CMAX
                       M               M      M      -      -
   1  740405    95   342.8       6    1.5   61.0    8.4   10.0
   2  740618   169   342.8       8    1.5   52.2    5.4    9.0
   3  740830   242   341.0       9     .0   51.9     .4    7.8
   4  741009   282   341.3      10     .0   53.4     .2    7.6
```

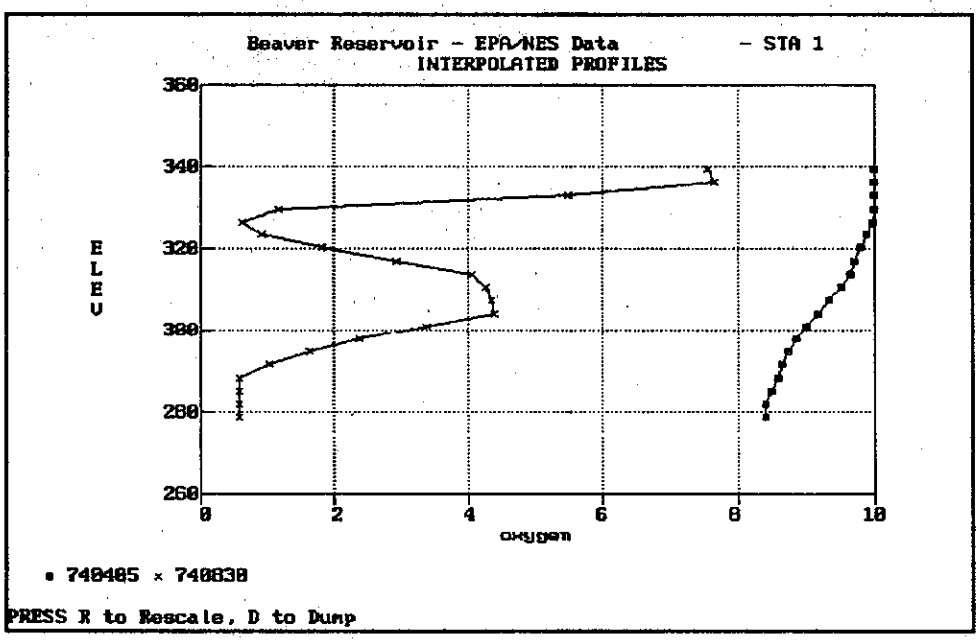
Above is an inventory of the oxygen and temperature data in the current window. Next, select the first and last sampling round to be used in oxygen depletion calculations. Generally, the first profile should be the first round after the onset of stratification, and the last profile should be the last round without anoxic conditions. See text for more details.

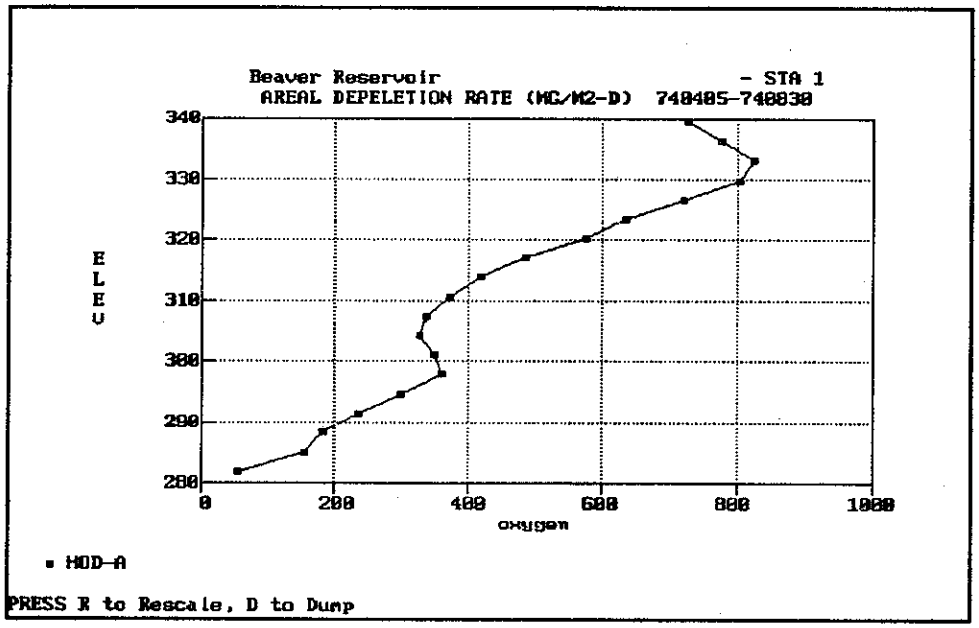
```
DEFINE SAMPLING ROUNDS FOR HOD CALCS
FIRST SAMPLING ROUND <##>?  1
LAST SAMPLING ROUND  <##>?  3

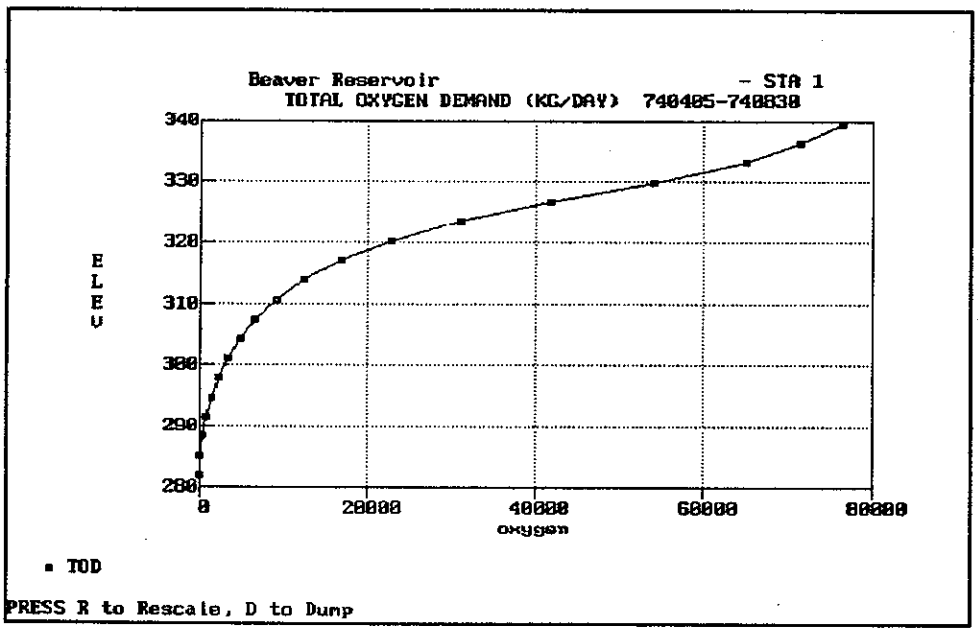
Vertical Profile Plots for the Selected Dates Follow.
Later, You Will Be Asked to Specify the Upper & Lower Boundaries
    of the Thermocline for Use in HOD Calculations.
        Press <Enter> to Continue
<H>
```

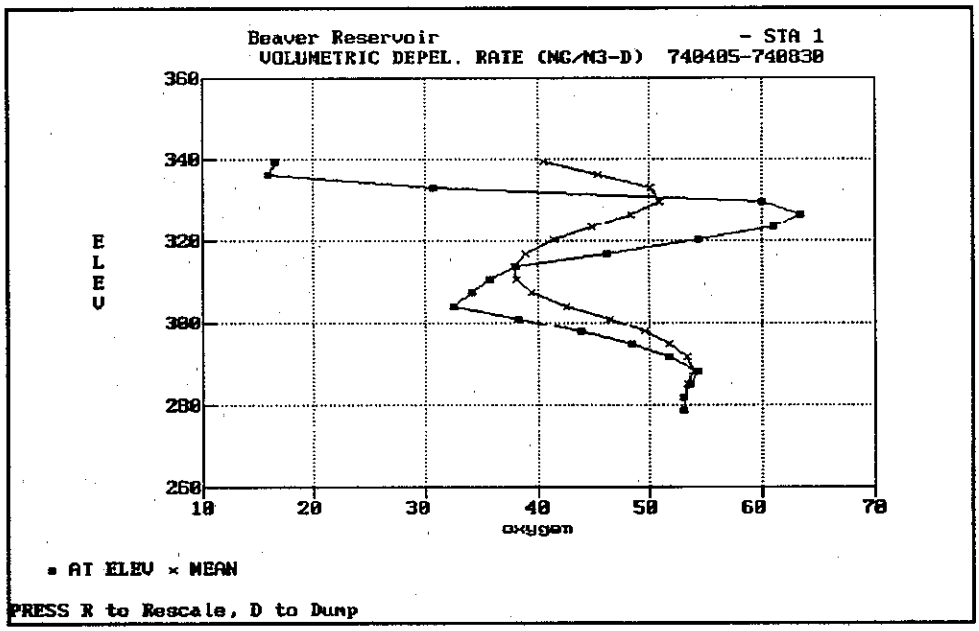
Five plots follow, showing vertical profiles of temperature, oxygen, areal oxygen depletion rate and total oxygen demand (below each elevation increment), and volumetric oxygen depletion rates. View the first plot (temperature) to select appropriate thermocline boundaries (top, bottom):


Beaver Reservoir - EPA/NES Data - STA 1
INTERPOLATED PROFILES
ELEV
360
340
320
300
280
260
5
10
15
20
25
30
temp
• 740405 × 740830
PRESS R to Rescale, D to Dump


Beaver Reservoir - EPA/NES Data - STA 1
INTERPOLATED PROFILES
ELEV
360
340
320
300
280
260
0
2
4
6
8
10
oxygen
• 740405 × 740830
PRESS R to Rescale, D to Dump


Beaver Reservoir - STA 1
AREAL DEPELETION RATE (MG/M2-D) 740405-740830
ELEV
340
330
320
310
300
290
280
0
200
400
600
800
1000
oxygen
MOD-A
PRESS R to Rescale, D to Dump


Beaver Reservoir - STA 1
TOTAL OXYGEN DEMAND (KG/DAY) 740405-740830
ELEV
340
330
320
310
300
290
280
0
20000
40000
60000
80000
oxygen
TOD
PRESS R to Rescale, D to Dump



The upper plot shows the total oxygen demand (kg/day) below each elevation. This may be useful for sizing hypolimnetic aerators. The lower plot shows volumetric oxygen depletion rate at each elevation and the mean depletion rate below each elevation.

Thermocline boundaries are defined in the following screen:

```
ENTER THERMOCLINE BOUNDARIES BETWEEN   278.8 AND   342.8 IN METERS
ELEV AT TOP OF HYPOLIMNION?   305
ELEV AT TOP OF METALIMNION?   325
```

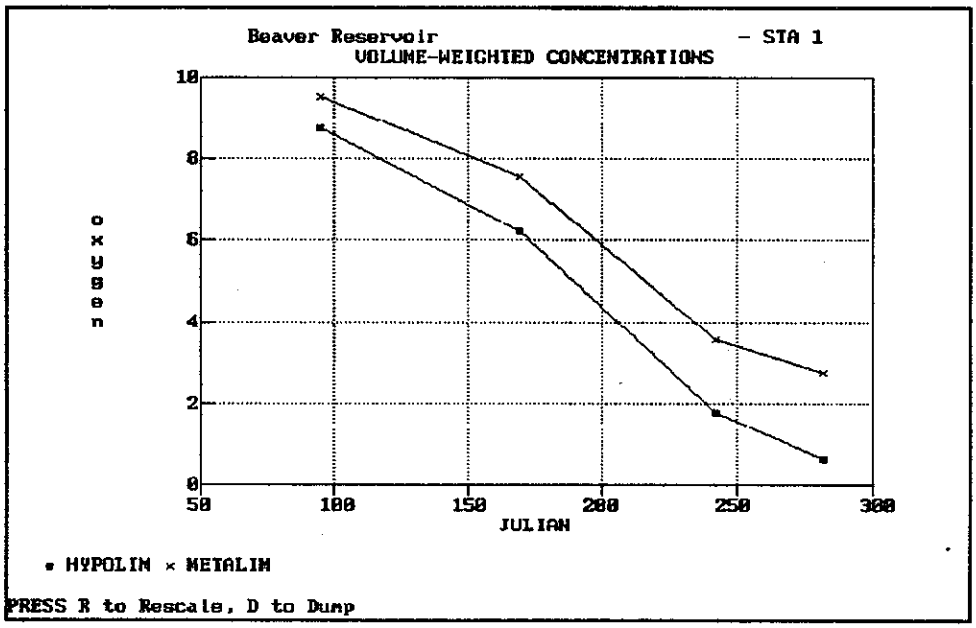
The following output table shows calculation results:

```
Beaver Reservoir                          COMPONENT:  2 oxygen
STATION:  1 above dam        RKM:  119.0  BASE ELEV:  279.4
DATES: 740405 TO 740830
STATISTIC                   HYPOLIMNION METALIMNION       BOTH
ELEVATION            M           305.00      325.00     325.00
SURFACE AREA        KM2           15.90       53.01      53.01
VOLUME              HM3          125.66      643.67     769.33
MEAN DEPTH           M            7.90       12.14      14.51
MAXIMUM DEPTH        M           26.23       20.00      46.23
INITIAL CONC        G/M3          8.93        9.70       9.57
FINAL CONC          G/M3          2.79        2.70       2.72
AREAL DEPL. RATE  MG/M2-DAY     330.03      578.02     677.02
VOL. DEPL. RATE   MG/M3-DAY      41.76       47.61      46.65
```

You may repeat the calculations using different thermocline boundaries, if desired.

```
TRY OTHER BOUNDARIES <0.=NO,1.=YES>?  0
```

The following plot shows the time series of volume-weighted mean oxygen concentrations in the hypolimnion and metalimnion. The slopes of these lines are proportional to the volume-weighted mean oxygen depletion rates.




```
View Calculation File ? n
```

Hit **y** *to view details of oxygen depletion calculations. Hit* **n** *to return to program menu.*

Following is a demonstration of the **Calculate/Summaries** *procedure. This procedure constructs a two-way table with columns defined by station/segment and rows defined by sampling round. First set the data window to include phosphorus:*

```
P R O F I L E - VERSION 4.5
Data      Window    Plot    Calculate    Utilities   Help     Quit
Date/Depth      Components      Stations      All      Reset

    Define Water Quality Components

MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
  VARIABLE
  temp
  oxygen
* total p
```

```
P R O F I L E - VERSION 4.5
Data      Window      Plot      Calculate      Utilities      Quit
HOD       Summaries   Options

     Summarize Water Quality Data - Calculate Area-Weighted Means

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

A help screen appears:

```
     Mixed-Layer Water Quality Summaries

     On the next screen, you will specify the data to be summarized.

     Set the DEPTH range to reflect the mixed layer of the reservoir.

     Set the SEASON range to reflect the growing season.

     Constraints:
        Maximum Samples = 4000
        Maximum Rows (Sampling Dates) = 200
        Maximum Columns (Stations or Segments) = 20

          PRESS KEY TO CONTINUE, <ESC> RETURN TO MENU                21
```

Set the date and depth ranges accordingly:

```
                PROFILE  DATA  WINDOW

SAMPLE DATE RANGE:   740405 TO 741009   <YYMMDD>

SEASON RANGE:        0      TO 0        <MMDD>

DEPTH RANGE:         0      TO 10      <METERS>
```

Results:

```
Columns = Segments
Cell Summaries = Medians
Output Format = Long
Beaver Reservoir

COMPONENT: total p , DEPTHS:     .0 TO   10.0 M
total p  SAMPLE FREQUENCIES:
SEGMENT        1      4      6      8     10     12 RESERV
DATE  WTS> .050   .100   .150   .250   .250   .200
-------------------------------------------------------
740405         4      4      3      3      3      3     20
740618         4      4      5      3      4      4     24
740830         4      4      4      3      3      3     21
741009         4      4      4      4      4      4     24
-------------------------------------------------------
SAMPLES       16     16     16     13     14     14     89
  DATES        4      4      4      4      4      4      4
```

```
total p  SUMMARY VALUES:
SEGMENT        1      4      6      8     10     12 RESERV
DATE  WTS> .050   .100   .150   .250   .250   .200
-----------------------------------------------------------
740405      67.0   47.0   37.0   36.0   16.0    9.0   28.4
740618      61.5   89.0   32.0   16.0    9.0    9.5   24.9
740830      49.5   41.5   21.0   15.0   12.0   12.0   18.9
741009      48.0   37.5   21.5   11.0   10.5   10.0   16.8
-----------------------------------------------------------
SAMPLES       16     16     16     13     14     14     89
  DATES        4      4      4      4      4      4
 MEDIANS    55.5   44.3   26.8   15.5   11.3    9.8   21.9
   MEANS    56.5   53.8   27.9   19.5   11.9   10.1   22.3
      CV    .164   .443   .284   .575   .254   .130   .241
CV(MEAN)    .082   .222   .142   .287   .127   .065   .121
```

The right-hand column contains reservoir mean values, weighted by the area of each segment. Select Calculate/Options to set other data-summary options.

Select **Help** *to view supplementary help screens in various categories.*

```
P R O F I L E - VERSION 4.5
Data    Window    Plot    Calculate    Utilities    Help    Quit

    Display Help Screens

MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

```
PRESS <ESC> TO QUIT
```

```
HELP TOPICS
INTRODUCTORY SCREENS
PROCEDURES
PLOTTING
PROGRAM MECHANICS
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Select **Quit** *to end session:*

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P R O F I L E - VERSION 4.5
Data    Window    Plot    Calculate    Utilities    Help    Quit

    End Profile Session

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4 BATHTUB

BATHTUB Overview

BATHTUB is designed to facilitate application of empirical eutrophication models to morphometrically complex reservoirs. The program performs water and nutrient balance calculations in a steady-state, spatially segmented hydraulic network that accounts for advective transport, diffusive transport, and nutrient sedimentation. Eutrophication-related water quality conditions (expressed in terms of total phosphorus, total nitrogen, chlorophyll *a*, transparency, organic nitrogen, nonortho-phosphorus, and hypolimnetic oxygen depletion rate) are predicted using empirical relationships previously developed and tested for reservoir applications (Walker 1985). To provide regional perspectives on reservoir water quality, controlling factors, and model performance, BATHTUB can also be configured for simultaneous application to collections or networks of reservoirs. As described in Chapter 1, applications of the program would normally follow use of the FLUX program for reducing tributary monitoring data and use of the PROFILE program for reducing pool monitoring data, although use of the data reduction programs is optional if independent estimates of tributary loadings and/or average pool water quality conditions are used.

The functions of the program can be broadly classified as diagnostic or predictive. Typical applications would include the following:

a. Diagnostic.

(1) Formulation of water and nutrient balances, including identification and ranking of potential error sources.

(2) Ranking of trophic state indicators in relation to user-defined reservoir groups and/or the CE reservoir database.

(3) Identification of factors controlling algal production.

b. Predictive.

(1) Assessing impacts of changes in water and/or nutrient loadings.

(2) Assessing impacts of changes in mean pool level.

(3) Estimating nutrient loadings consistent with given water quality management objectives.

The program generates output in various formats, as appropriate for specific applications. Predicted confidence limits can be calculated for each output variable using a first-order error analysis scheme that incorporates effects of uncertainty in model input values (e.g., tributary flows and loadings, reservoir morphometry, monitored water quality) and inherent model errors.

A detailed description of the following topics is given in the remaining sections of this chapter.

a. Theory

b. Program operation.

c. Application steps.

d. Procedure outline.

e. Data entry screens.

f. Documented session.

g. Instructional cases.

These and other features of the program may be examined by reviewing the example data sets supplied at the end of this chapter and by viewing help screens supplied with the program.

Theory

Introduction

A flow diagram for BATHTUB calculations is given in Figure 4.1. This section describes calculations performed in the model core:

a. Water balance.

b. Nutrient balance.

c. Eutrophication response.

Using a first-order error analysis procedure (Walker 1982), the model core is executed repeatedly in order to estimate output sensitivity to each input

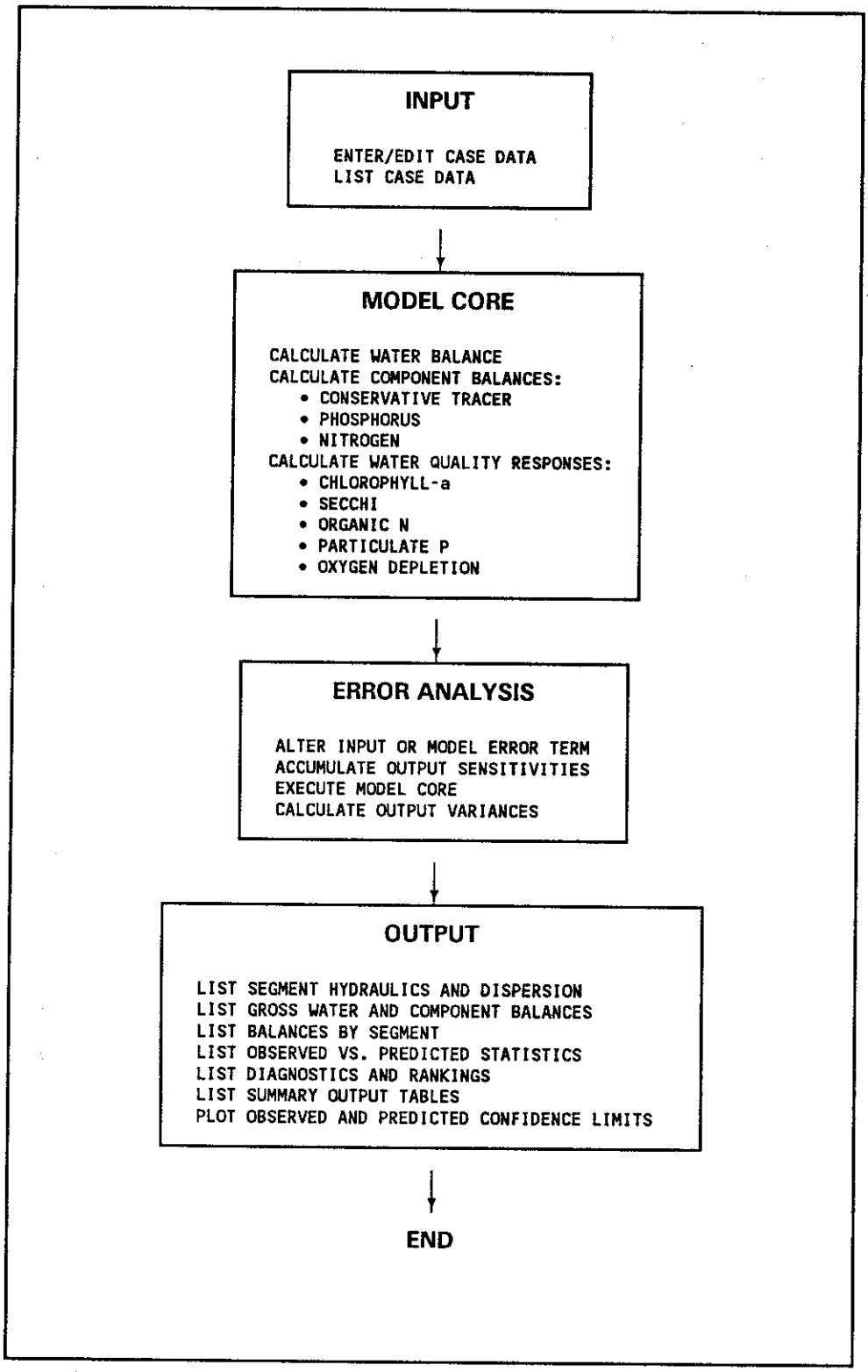


Figure 4.1. Schematic of BATHTUB calculations

variable and submodel and to develop variance estimates and confidence limits for each output variable. The remainder of the program consists of graphic and tabular output routines designed to summarize results.

Control pathways for predicting nutrient levels and eutrophication response in a given model segment are illustrated in Figure 4.2.

Predictions are based upon empirical models which have been calibrated and tested for reservoir applications (Walker 1985). Model features are documented as follows: symbol definitions (Table 4.1), model equations and options (Table 4.2), supplementary response models (Table 4.3), error statistics (Table 4.4), and diagnostic variables (Table 4.5).

As listed in Table 4.2, several options are provided for modeling nutrient sedimentation, chlorophyll *a*, and transparency. In each case, Models 1 and 2 are the most general formulations, based upon model testing results. Alternative models are included to permit sensitivity analyses and application of the program under various data constraints (see Table 4.2). Table 4.3 specifies submodels for predicting supplementary response variables (organic nitrogen, particulate phosphorus, principal components, oxygen depletion rates, trophic state indices, algal nuisance frequencies). Error statistics for applications of the model network to predict spatially averaged conditions are summarized in Table 4.4.

The following sections describe underlying theory. The development and testing of the network equations (Walker 1985) should be reviewed prior to using the program.

Segmentation

Through appropriate configuration of model segments, BATHTUB can be applied to a wide range of reservoir morphometries and management problems. Figure 4.3 depicts segmentation schemes in six general categories:

a. Single reservoir, spatially averaged.

b. Single reservoir, segmented.

c. Partial reservoir or embayment, segmented.

d. Single reservoir, spatially averaged, multiple scenario.

e. Collection of reservoirs, spatially averaged.

f. Network of reservoirs, spatially averaged.

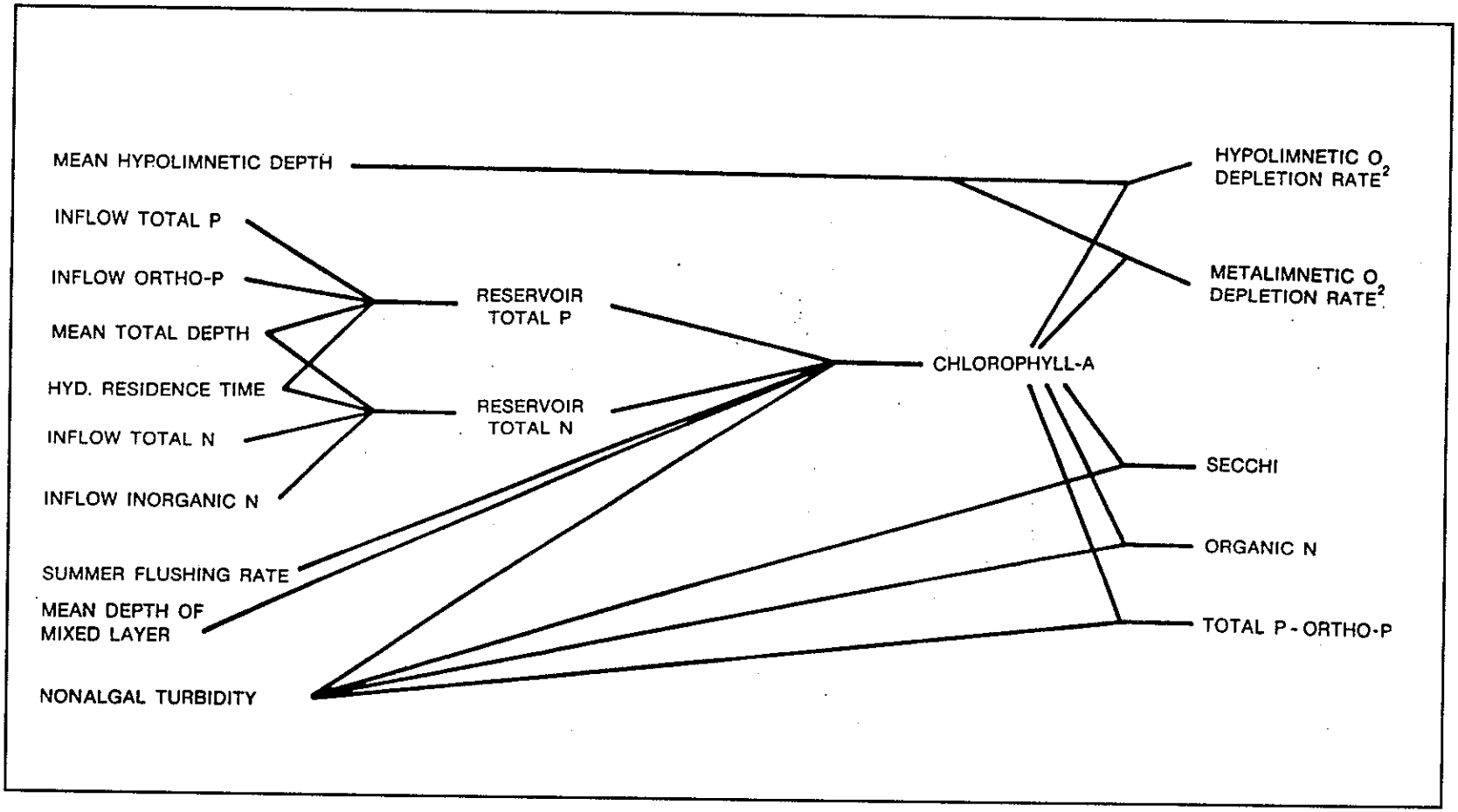


Figure 4.2. Control pathways in empirical eutrophication models developed for CE reservoir applications

Table 4.1
Symbol Definitions

a	=	Nonalgal Turbidity (m^{-1}) = 1/S - 0.025 B
As	=	Surface Area of Segment (km^2)
Ac	=	Cross-Sectional Area of Segment (km*m)
A1	=	Intercept of Phosphorus Sedimentation Term
A2	=	Exponent of Phosphorus Sedimentation Term
B1	=	Intercept of Nitrogen Sedimentation Term
B2	=	Exponent of Nitrogen Sedimentation Term
B	=	Chlorophyll *a* Concentration (mg/m^3)
Bm	=	Reservoir Area-Weighted Mean Chlorophyll *a* Concentration (mg/m^3)
Bp	=	Phosphorus-Potential Chlorophyll *a* Concentration (mg/m^3)
Bx	=	Nutrient-Potential Chlorophyll *a* Concentration (mg/m^3)
CB	=	Calibration Factor for Chlorophyll *a*
CD	=	Calibration Factor for Dispersion
CN	=	Calibration Factor for N Sedimentation Rate
CO	=	Calibration Factor for Oxygen Depletion
CP	=	Calibration Factor for P Sedimentation Rate
CS	=	Calibration Factor for Secchi Depth
D	=	Dispersion Rate (km^2/year)
Dn	=	Numeric Dispersion Rate (km^2/year)
E	=	Diffusive Exchange Rate between Adjacent Segments (hm^3/year)
Fs	=	Summer Flushing Rate = (Inflow-Evaporation)/Volume ($year^{-1}$)
Fin	=	Tributary Inorganic N Load/Tributary Total N Load
Fot	=	Tributary Ortho-P Load/Tributary Total P Load
FD	=	Dispersion Calibration Factor (applied to all segments)
G	=	Kinetic Factor Used in Chlorophyll *a* Model
HODv	=	Near-Dam Hypolimnetic Oxygen Depletion Rate (mg/m^3-day)
L	=	Segment Length (km)
MODv	=	Near-Dam Metalimnetic Oxygen Depletion Rate (mg/m^3-day)
N	=	Reservoir Total Nitrogen Concentration (mg/m^3)

(Continued)

Table 4.1 (Concluded)

Ni	=	Inflow Total Nitrogen Concentration (mg/m^3)
Nin	=	Inflow Inorganic N Concentration (mg/m^3)
Nia	=	Inflow Available N Concentration (mg/m^3)
Ninorg	=	Inorganic Nitrogen Concentration (mg/m^3)
Norg	=	Organic Nitrogen Concentration (mg/m^3)
P	=	Total Phosphorus Concentration (mg/m^3)
Pi	=	Inflow Total P Concentration (mg/m^3)
Pio	=	Inflow Ortho-P Concentration (mg/m^3)
Pia	=	Inflow Available P Concentration (mg/m^3)
Portho	=	Ortho-Phosphorus Concentration (mg/m^3)
PC-1	=	First Principal Component of Response Measurements
PC-2	=	Second Principal Component of Response Measurements
Q	=	Segment Total Outflow (hm^3/year)
QS	=	Surface Overflow Rate (m/year)
S	=	Secchi Depth (m)
T	=	Hydraulic Residence Time (years)
TSIp	=	Carlson Trophic State Index (Phosphorus)
TSIc	=	Carlson Trophic State Index (Chlorophyll *a*)
TSIs	=	Carlson Trophic State Index (Transparency)
U	=	Mean Advective Velocity (km/year)
V	=	Total Volume (hm^3)
W	=	Mean Segment Width (km)
Wp	=	Total Phosphorus Loading (kg/year)
Wn	=	Total Nitrogen Loading (kg/year)
Xpn	=	Composite Nutrient Concentration (mg/m^3)
Z	=	Total Depth (m)
Zx	=	Maximum Total Depth (m)
Zh	=	Mean Hypolimnetic Depth of Entire Reservoir (m)
Zmix	=	Mean Depth of Mixed Layer (m)

Table 4.2
BATHTUB Model Options

Conservative Substance Balance

Model 0: Do Not Compute (Set Predicted = Observed) [default]

Model 1: Compute Mass Balances

Phosphorus Sedimentation

Unit P Sedimentation Rate (mg/m^3-year) = $CP\ A1\ P^{A2}$

Solution for Mixed Segment:

Second-Order Models (A2 = 2)

$$P = [-1 + (1 + 4\ CP\ A1\ Pi\ T)^{0.5}]/(2\ CP\ A1\ T)$$

First-Order Models (A2 = 1)

$$P = Pi/(1 + CP\ A1\ T)$$

Model	A1	A2
0 - Do Not Compute (Set Predicted = Observed)	--	--
1 - Second-Order, Available P [default]	0.17 Qs/(Qs + 13.3)	2
Qs = MAX(Z/T,4)		
Inflow Available P = 0.33 Pi + 1.93 Pio		
2 - Second-Order Decay Rate Function	$0.056\ Fot^{-1}Qs/(Qs + 13.3)$	2
3 - Second-Order	0.10	2
4 - Canfield and Bachman (1981)	$0.11\ (Wp/V)^{0.59}$	1
5 - Vollenweider (1976)	$T^{-0.5}$	1
6 - Simple First-Order	1	1
7 - First-Order Settling	1/Z	1

(Sheet 1 of 4)

Note: For purposes of computing effective rate coefficients (A1), Qs, Wp, Fot, T, and V are evaluated separately for each segment group based upon external loadings and segment hydraulics.

Table 4.2 (Continued)

Nitrogen Sedimentation

Unit N Sedimentation Rate (mg/m^3-year) = CN B1 N^{B2}

Solutions for Mixed Segment:

Second-Order Models (B2 = 2)

$$N = [-1 + (1 + 4\ CN\ B1\ Ni\ T)^{0.5}]/(2\ CN\ B1\ T)$$

First-Order Models (B2 = 1)

$$N = Ni/(1 + CN\ B1\ T)$$

Model	B1	B2
0 - Do Not Compute (Set Predicted = Observed)	--	--
1 - Second-Order, Available N [default] QS = Maximum (Z/T,4) Inflow Available N=0.59 Ni + 0.79 Nin	0.0045 Qs/(Qs + 7.2)	2
2 - Second-Order Decay Rate Function Qs = Maximum (Z/T,4) Fin = Tributary Inorganic N/Total N Load	0.0035 $Fin^{-0.59}$Qs/(Qs+17.3)	2
3 - Second-Order	0.00315	2
4 - Bachman (1980)/Volumetric Load	0.0159 $(Wn/V)^{0.59}$	1
5 - Bachman (1980)/Flushing Rate	0.693 $T^{-0.55}$	1
6 - Simple First Order	1	1
7 - First-Order Settling	1/Z	1

(Sheet 2 of 4)

Note: For purposes of computing effective rate coefficients (B1), Qs, Wn, Fin, T, and V are evaluated separately for each segment group based upon external loadings and segment hydraulics.

Nitrogen Model 1 differs slightly from that developed in Walker (1985). The coefficients have been adjusted so that predictions will be unbiased if inflow inorganic nitrogen data are not available (inflow available N = inflow total N). These adjustments have negligible influence on model error statistics.

Table 4.2 (Continued)

Mean Chlorophyll *a*	Applicability
Model 0: Do Not Compute	
Model 1: N, P, Light, Flushing Rate $Xpn = [P^{-2} + ((N-150)/12)^{-2}]^{-0.5}$ $Bx = Xpn^{1.33}/4.31$ $G = Zmix\ (0.14 + 0.0039\ Fs)$ $B = CB\ Bx/[(1 + 0.025\ Bx\ G)\ (1 + Ga)]$	General
Model 2: P, Light, Flushing Rate [default] $Bp = p^{1.37}/4.88$ $G = Zmix\ (0.19 + 0.0042\ Fs)$ $B = CB\ Bp/[(1 + 0.025\ Bp\ G)\ (1 + Ga)]$	Ninorg/Portho > 7 (N-150)/P > 12
Model 3: P, N, Low-Turbidity $B = CB\ 0.2\ Xpn^{1.25}$	$a < 0.4\ m^{-1}$ Fs < 25 1/year
Model 4: P, Linear $B = CB\ 0.28\ P$	a < 0.9 1/m Ninorg/Portho > 7 (N-150)/P > 12 Fs < 25 1/year
Model 5: Jones and Bachman (1976) $B = CB\ 0.081\ P^{1.46}$	$a < 0.4\ m^{-1}$ Ninorg/Portho > 7 (N-150)/P > 12 Fs < 25 1/year

Secchi Depth	Applicability
Model 0: Do Not Compute	
Model 1: Secchi vs. Chl *a* and Turbidity [default] $S = CS/(a + 0.025\ B)$	General
Model 2: Secchi vs. Composite Nutrient $S = CS\ 16.2\ Xpn^{-0.79}$	General
Model 3: Secchi vs. Total P $S = CS\ 17.8\ P^{-0.76}$	Ninorg/Portho > 7

Dispersion Models - Estimation of Exchange Flows Between Adjacent Segments

Model 0: Do Not Compute
$E = 0.$

Model 1: Fischer et al. (1979) Dispersion Equation, Walker (1985) [default]

Width	$W = As/L$
Cross-Section	$Ac = W\ Z$
Velocity	$U = Q/Ac$
Dispersion	$D = CD\ 100\ W^2\ Z^{-0.84}$ Maximum (U,1)
Numeric Dispersion	$Dn = U\ L/2$
Exchange	$E = MAX(D-Dn, 0)\ Ac/L$

Model 2: Fixed Dispersion Rate
Same as Model 1, except with fixed dispersion rate of 1,000 km^2/year
$D = 1{,}000\ CD$

(Sheet 3 of 4)

Table 4.2 (Concluded)

Dispersion Models (Continued)

Model 3: Input Exchange Rates Directly
E = CD

Model 4: Fischer Equation, Not Adjusted for Numeric Dispersion
E = D Ac/L (D as defined in Model 1)

Model 5: Constant Dispersion Coefficient, Not Adjusted for Numeric Dispersion
E = 1,000 CD Ac/L

Note: For all options, E = 0. always for segments discharging out of network (outflow segment number = 0).

Phosphorus Calibration Method

Option 0: Multiply Estimated Sedimentation Rates by Calibration Factors [default]

Option 1: Multiply Estimated Concentrations by Calibration Factors

Nitrogen Calibration Method

Option 0: Multiply Estimated Sedimentation Rates by Calibration Factors [default]

Option 1: Multiply Estimated Concentrations by Segment Calibration Factors

Note: Segment calibration factors (defined via Case Edit Segment) are always applied to sedimentation rates. The above options apply only to global calibration factors (defined via Case Edit Mcoefs).

Use of Availability Factors

Option 0: Do Not Apply Availability Factors

Calculate nutrient balances based upon Total P and Total N only.

Option 1: Apply Availability Factors to P & N Model 1 Only [default]

When P Model 1 or N Model 1 is selected, calculate nutrient balances based upon Available nutrient loads:
Inflow Available P = 0.22 Pi + 1.93 Pio
Inflow Available N = 0.59 Ni + 0.79 Nin
When other P or N models are selected, calculate nutrient balances based upon Total P and Total N.

Option 3: Apply Availability Factors to all P & N models except Model 2.

Calculation of Nutrient Mass-Balance Tables

Option 0: Use Predicted Segment Concentrations to Calculate Outflow and Storage Terms [default]

Option 1: Use Observed Segment Concentrations to Calculate Outflow and Storage Terms

(Sheet 4 of 4)

Table 4.3
Supplementary Response Models

Organic Nitrogen

$$Norg = 157 + 22.8\ B + 75.3\ a$$

Total P - Ortho P

$$P - Portho = Maximum\ [\ -4.1 + 1.78\ B + 23.7\ a\ ,\ 1\ ]$$

Hypolimnetic Oxygen Depletion Rate (Near-Dam)

$$HODv = 240\ Bm^{.5} / Zh \quad (for\ Zh > 2\ m)$$

Metalimnetic Oxygen Depletion Rate (Near-Dam)

$$MODv = 0.4\ HODv\ Zh\ 0.38$$

Principal Components

With Chl *a*, Secchi, Nutrient, & Organic Nitrogen Data:

$$PC\text{-}1 = 0.554\ log(B) + 0.359\ log(Norg) + 0.583\ log(Xpn) - 0.474\ log(S)$$

$$PC\text{-}2 = 0.689\ log(B) + 0.162\ log(Norg) - 0.205\ log(Xpn) + 0.676\ log\ (S)$$

With Chl *a* and Secchi Data Only:

$$PC\text{-}1 = 1.47 + 0.949\ log(B) - 0.932\ log(S)$$

$$PC\text{-}2 = 0.13 + 0.673\ log(B) + 0.779\ log(S)$$

Trophic State Indices (Carlson 1977)

$$TSIp = 4.15 + 14.42\ ln(P)$$

$$TSIc = 30.6 + 9.84\ ln(B)$$

$$TSIs = 60.0 - 14.41\ ln(S)$$

Algal Nuisance Level Frequencies (Walker 1984)

Percent of time during growing season that Chl *a* exceeds bloom criteria of 10, 20, 30, 40, or 50 ppb.

Calculated from Mean Chl *a* assuming log-normal frequency distribution with temporal coefficient of variation = 0.62

Table 4.4
Error Statistics for Model Network Applied to Spatially Averaged CE Reservoir Data

Variable	Error CV		$R^{2\dagger}$	Comment
	Total*	Model**		
Total phosphorus	0.27	0.45††	0.91	Models 1, 2
Total nitrogen	0.22	0.55††	0.88	Models 1, 2
Chlorophyll *a*	0.35	0.26	0.79	Models 1, 2
	0.47	0.37	-	Models 3-6
Secchi depth	0.28	0.10	0.89	Model 1
	0.29	0.19	-	Model 2
Organic nitrogen	0.25	0.12	0.75	
Total p - Ortho p	0.37	0.15	0.87	
Hypolimnetic oxygen depletion	0.20	0.15	0.90	‡
Metalimnetic oxygen depletion	0.33	0.22	0.76	‡

Note: Error statistics for CE model development data set (n = 40).

* Total = total error (model + data components).
** Model = Estimated Model Error Component.
† R^2 = percent of observed variance explained.
†† Model error CV applied to nutrient sedimentation rates (versus concentrations).
‡ Volumetric oxygen depletion (n = 16).

Segments can be modeled independently or linked in a network. Each segment is defined in terms of its morphometry (area, mean depth, length, mixed layer depth, hypolimnetic depth) and observed water quality (optional). Morphometric features refer to average conditions during the period being simulated. Segment linkage is defined by assigning each segment an ID number (from 1 to 39) and specifying the ID number of the segment that is immediately downstream of each segment. Multiple external sources and/or withdrawals can be specified for each segment. With certain limitations, combinations of the above schemes are also possible. Characteristics and applications of each segmentation scheme are discussed below.

Table 4.5
Diagnostic Variables and Their Interpretation

Variable	Units	Explanation
TOTAL P	mg/m^3	Total phosphorus concentration CE distrib (MEAN = 48, CV = 0.90, MIN = 9.9, MAX = 274) Measure of nutrient supply under P-limited conditions
TOTAL N	mg/m^3	Total nitrogen concentration CE distr (MEAN = 1002, CV = 0.64, MIN = 243, MAX = 4306) Measure of nutrient supply under N-limited conditions
C. NUTRIENT	mg/m^3	Composite nutrient concentration CE distr (MEAN = 36, CV = 0.80, MIN = 6.6, MAX = 142) Measure of nutrient supply independent of N versus P limitation; equals total P at high N/P ratios
CHL A	mg/m^3	Mean chlorophyll *a* concentration CE distrib (MEAN = 9.4, CV = 0.77, MIN = 2, MAX = 64) Measure of algal standing crop based upon photosynthetic pigment
SECCHI	m	Secchi depth CE distrib (MEAN = 1.1, CV=0.76, MIN = 0.19, MAX = 4.6) Measure of water transparency as influenced by algae and nonalgal turbidity
ORGANIC N	mg/m^3	Organic nitrogen concentration CE dist (MEAN = 474, CV = 0.51, MIN = 186, MAX = 1510) Portion of nitrogen pool in organic forms; generally correlated with chlorophyll *a* concentration
P-ORTHOP	mg/m^3	Total phosphorus - Ortho phosphorus CE distrib (MEAN = 30, CV = 0.95, MIN = 4, MAX = 148) Phosphorus in organic or particulate forms correlated with chlorophyll *a* and nonalgal turbidity
HODv	mg/m^3-day	Hypolimnetic oxygen depletion rate CE distrib (MEAN = 77, CV = 0.75, MIN = 36, MAX = 443) Rate of oxygen depletion below thermocline; related to organic supply from settling of algae, external organic sediment loads, and hypolimnetic depth For HOD-V > 100; hypolimnetic oxygen supply depleted within 120 days after onset of stratification
MODv	mg/m^3-day	Metalimnetic oxygen depletion rate CE distrib (MEAN = 68, CV = 0.71, MIN = 25, MAX = 286) Rate of oxygen depletion within thermocline; generally more important than HODv in deeper reservoirs (mean hypolimnetic depth >20 m)
ANTILOG PC-1	--	First principal component of reserv. response variables (Chlorophyll *a*, Secchi, Organic N, Composite Nutrient) CE distrib (MEAN = 245, CV =1.3, MIN = 18, MAX = 2460) Measure of nutrient supply: Low: PC-1 < 50 low nutrient supply low eutrophication potential High: PC-1 > 500 high nutrient supply high eutrophication potential

(Sheet 1 of 3)

Notes: CE distribution based upon 41 reservoirs used in development and testing of the model network (MEAN, CV = geometric mean and coefficient of variation). Low and high values are typical benchmarks for interpretation.

Table 4.5 (Continued)

Variable	Units	Explanation
ANTILOG PC-2	--	Second principal component of reserv. response variables CE distrib (MEAN = 6.4, CV =0.53, MIN = 1.6, MAX = 13.4) Nutrient association with organic vs. inorganic forms; related to light-limited areal productivity Low: PC-2 < 4 turbidity-dominated, light-limited, low nutrient response High: PC-2 > 10 algae-dominated, light unimportant, high nutrient response
(N-150)/P	--	(Total N - 150)/Total P ratio CE distrib. (MEAN = 17, CV = 0.68, MIN = 4.7, MAX = 73) Indicator of limiting nutrient Low: (N-150)/P < 10-12 nitrogen-limited High: (N-150)/P > 12-15 phosphorus-limited
INORGANIC N/P Ratio	--	Inorganic nitrogen/ortho-phosphorus ratio CE distrib. (MEAN = 30, CV = 0.99, MIN = 1.6, MAX = 127) Indicator of limiting nutrient Low: N/P < 7-10 nitrogen-limited High: N/P > 7-10 phosphorus-limited
TURBIDITY	m^{-1}	Nonalgal turbidity (1/SECCHI - 0.025 x CHL-A) CE distrib. (MEAN = 0.61, CV=0.88, MIN = 0.13,MAX = 5.2) Inverse Secchi corrected for light extinction by Chl *a* Reflects color and/or inorganic suspended solids Influences algal response to nutrients: Low: Turbidity < 0.4 allochthonous particulates unimportant high algal response to nutrients High: Turbidity > 1 allochthonous particulates possibly important low algal response to nutrients
ZMIX * TURBIDITY	--	Mixed-layer depth x turbidity CE distrib. (MEAN = 3.2, CV = 0.78, MIN = 1.0, MAX = 17) Effect of turbidity on light intensity in mixed layer Low: < 3 light availability high; turbidity unimportant high algal response to nutrients High: > 6 light availability low; turbidity important low algal response to nutrients
ZMIX/ SECCHI	--	Mixed-layer depth/Secchi depth (dimensionless) CE distrib (MEAN = 4.8, CV = 0.58, MIN = 1.5, MAX = 19) Inversely proportional to mean light intensity in mixed layer for a given surface light intensity: Low: < 3 light availability high high algal response to nutrients expected High: > 6 light availability low low algal response to nutrients expected

(Sheet 2 of 3)

Table 4.5 (Concluded)

Variable	Units	Explanation
CHL A SECCHI	--	Chlorophyll *a* x transparency (mg/m^2) CE distrib (MEAN = 10, CV = 0.71, MIN = 1.8, MAX = 31) Partitioning of light extinction between algae turbidity Measure of light-limited productivity Correlated with PC-2 (second principal component) Low: < 6 turbidity-dominated, light-limited low nutrient response expected High: > 16 algae-dominated, nutrient-limited high nutrient response expected
CHL A TOTAL P	--	Mean Chlorophyll *a* / Mean Total P CE distrib (MEAN = 0.20, CV=0.64, MIN=0.04, MAX = 0.60) Measure of algal use of phosphorus supply Related to nitrogen-limited and light-limitation factors Low: < 0.13 low phosphorus response algae limited by N, light, or flushing rate High: > 0.40 high phosphorus response (northern lakes) N, light, and flushing unimportant P limited (typical of northern lakes)
TSI-P TSI-B TSI-S	--	Trophic State Indices (Carlson 1977) Developed from Northern Lake Data Sets Calculated from P, Chl *a*, and Secchi Depths TSI < 40 "Oligotrophic" 41 < TSI < 50 "Mesotrophic" 51 < TSI < 70 "Eutrophic" TSI > 70 "Hypereutrophic"
FREQ > 10% FREQ > 20% FREQ > 30% FREQ > 40% FREQ > 50% FREQ > 60%		Algal Nuisance Frequencies or Bloom Frequencies Estimated from Mean Chlorophyll *a* Percent of Time During Growing Season that Chl *a* Exceeds 10, 20, 30, 40, 50, or 60 ppb Related to Risk or Frequency of Use Impairment "Blooms" generally defined at Chl *a* > 30-40 ppb

(Sheet 3 of 3)

Scheme 1 (Figure 4.3) is the simplest configuration. It is applicable to reservoirs in which spatial variations in nutrient concentrations and related trophic state indicators are relatively unimportant. It can also be applied to predict area-weighted mean conditions in reservoirs with significant spatial variations. This is the simplest type of application, primarily because transport characteristics within the reservoir (particularly, longitudinal dispersion) are not considered. The development of submodels for nutrient sedimentation and eutrophication response has been based primarily upon application of this segmentation scheme to spatially averaged data from 41 CE reservoirs (Walker 1985).

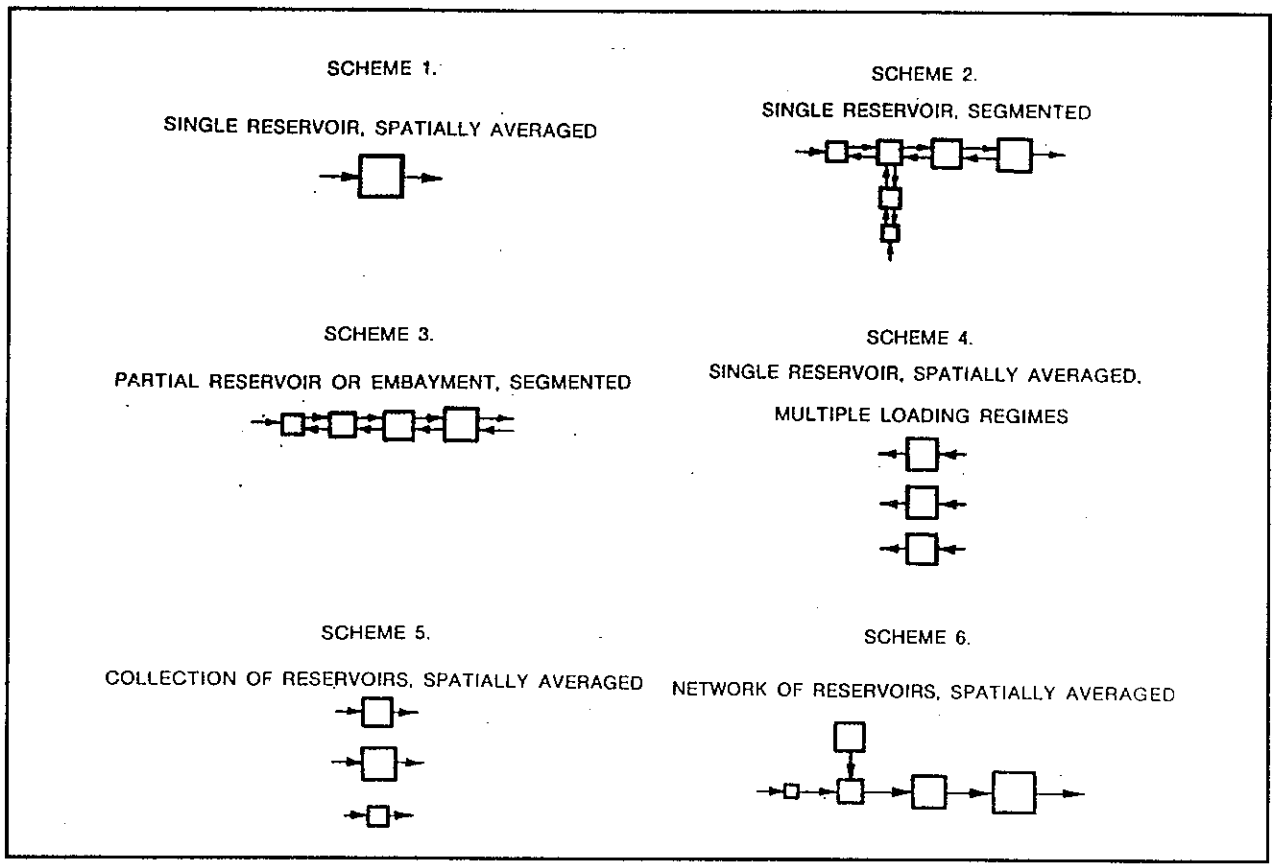


Figure 4.3. BATHTUB segmentation schemes

Scheme 2 involves dividing the reservoir into a network of segments for predicting spatial variations in water quality. Segments represent different areas of the reservoir (e.g., upper pool, midpool, near dam). Longitudinal nutrient profiles are predicted based upon simulations of advective transport, diffusive transport, and nutrient sedimentation. Reversed arrows in Figure 4.3 reflect simulation of longitudinal dispersion. Branches in the segmentation scheme reflect major tributary arms or embayments. Multiple and higher order branches are also permitted. Segment boundaries can be defined based upon consideration of the following:

a. Reservoir morphometry.

b. Locations of major inflows and nutrient sources.

c. Observed spatial variations in water quality.

d. Locations of critical reservoir use areas.

e. Numeric dispersion potential (calculated by the program).

If pool monitoring data are available, spatial displays generated by PROFILE can be useful for identifying appropriate model segmentation. A degree of subjective judgment is normally involved in specifying segment boundaries, and sensitivity to alternative segmentation schemes should be investigated. Sensitivity to assumed segmentation should be low if longitudinal transport characteristics are adequately represented. Experience with the program indicates that segment lengths on the order of 5 to 20 km are generally appropriate. Segmentation should be done conservatively (i.e., use the minimum number required for each application).

Scheme 3 illustrates the use of BATHTUB for modeling partial reservoirs or embayments. This is similar to Scheme 2, except the entire reservoir is not being simulated and the downstream water quality boundary condition is fixed. Diffusive exchange with the downstream water body is represented by the bidirectional arrows attached to the last (most downstream) segment. An independent estimate of diffusive exchange with the downstream water body is required for this type of application.

Scheme 4 involves modeling multiple loading scenarios for a single reservoir in a spatially averaged mode. Each "segment" represents the same reservoir, but under a different "condition," as defined by external nutrient loading, reservoir morphometry, or other input variables. This scheme is useful primarily in a predictive mode for evaluation and rapid comparison of alternative management plans or loading scenarios. For example, Segment 1 might reflect existing conditions; Segment 2 might reflect projected future loadings as a result of land development; and Segment 3 might reflect projected future loadings with specific control options. By defining segments to reflect a wide range of loading conditions, loadings consistent with specific water quality objectives (expressed in terms of mean phosphorus concentration, chlorophyll *a*, and/or transparency) can be identified. One limitation of Scheme 4 is that certain input variables, namely precipitation, evaporation, and change in storage, are assumed to be constant for each segment. If year-to-year variations in these factors are significant, a separate input file should be constructed for each year.

Scheme 5 involves modeling a collection of reservoirs in a spatially averaged mode. Each segment represents a different reservoir. This is useful for regional assessments of reservoir conditions (i.e., rankings) and evaluations of model performance. Using this scheme, a single file can be set up to include input conditions (water and nutrient loadings, morphometry, etc.) and observed water quality conditions for each reservoir in a given region (e.g., state, ecoregion). As for Scheme 4, a separate input file must be constructed for each reservoir if there are significant differences in precipitation, evaporation, or change in storage across reservoirs.

Scheme 6 represents a network of reservoirs in which flow and nutrients can be routed from one impoundment to another. Each reservoir is modeled in a spatially averaged mode. For example, this scheme could be used to represent a network of tributary and main stem impoundments. This type of

application is feasible in theory but has been less extensively tested than those described above. One limitation is that nutrient losses in streams linking the reservoirs are not directly represented. Such losses may be important in some systems, depending upon such factors as stream segment length and time of travel. In practice, losses in transport could be approximately handled by defining "stream segments," provided that field data are available for calibration of sedimentation coefficients (particularly in the case of nitrogen). Networking of reservoirs is most reliable for mass balances formulated on a seasonal basis and for reservoirs that are unstratified or have surface outlets.

As illustrated in Figure 4.3, a high degree of flexibility is available for specifying model segments. Combinations of schemes are also possible within one input file. While each segment is modeled as vertically mixed, BATHTUB is applicable to stratified systems because the formulations have been empirically calibrated to data from a wide variety of reservoir types, including well-mixed and vertically stratified systems. Effects of vertical variations are incorporated in the model parameter estimates and error terms.

Segment groups

As indicated in Table 4.2, nutrient sedimentation coefficients may depend upon morphometric and hydrologic characteristics. To provide consistency with the data sets used in model calibration, segments must be aggregated for the purpose of computing effective sedimentation rate coefficients (A1 and B1 in Table 4.2). A "Segment Group Number" is defined for this purpose. Rate-coefficient computations are based upon the following variables summarized by segment group:

a. Surface overflow rate.

b. Flushing rate (or residence time).

c. Total external nutrient load.

d. Tributary total nutrient load.

e. Tributary ortho or inorganic nutrient load.

Flushing rate is also used in chlorophyll *a* Models 1 and 2. Area-weighted mean chlorophyll *a* values are computed for each segment group and used in the computation of hypolimnetic oxygen depletion rates (see Table 4.3).

Group numbers are integers ranging from 1 up to the total number of segments defined for the current case. Generally, if a case involves simulation of a single reservoir with multiple segments, all segments should be assigned the same group number (1). If the segments represent reservoir regions (tributary arms) with distinctly different morphometric, hydrologic, and water quality

characteristics, different group numbers can be assigned to each region. If the case involves simulation of multiple reservoirs (Schemes 5 or 6 in Figure 4.3), different group numbers are assigned to each reservoir.

Tributaries

Multiple of external inflows ('Tributaries') can be specified for any model segment. Tributaries are identified by name and a sequence number between 1 and 99. Each tributary is assigned to a specific segment number and classified using the following 'Type Codes':

1 Monitored Inflow
2 Nonpoint Inflow
3 Point-Source Inflow
4 Outflow or Withdrawal
5 Internal Load
6 Diffusive Source

Type 1 describes tributaries with monitored inflows and concentrations. Type 2 describes tributaries or watershed areas that are not monitored; inflow volumes and concentrations are estimated from user-defined land-use categories and export coefficients. In order to invoke this tributary type, the user must supply independent estimates of export coefficients (runoff (m/year) and typical runoff concentrations for each land use) developed from regional data. Type 3 describes point sources (e.g., wastewater treatment plant effluents) that discharge directly to the reservoir. Type 4 describes measured outflows or withdrawals; these are optional, since the model predicts outflow from the last segment based upon water-balance calculations. Specification of outflow streams is useful for checking water-balance calculations (by comparing observed and predicted outflow volumes). Type 5 can be used to define internal nutrient loading rates (recycling from bottom sediments); this option would be invoked in rare circumstances where independent estimates of sediment nutrient fluxes are available. Type 6 defines diffusive exchange with downstream water bodies in simulating embayments (e.g., Scheme 3 in Figure 4.3).

Transport channels

In normal segmentation schemes, outflow from each segment discharges to the next downstream segment or out of the system. An option for specifying additional advective and/or diffusive transport between any pair of segments is also provided. A maximum of 10 'Transport Channels' can be defined for this purpose. Independent measurements or estimates of advective and/or diffusive flow are required to invoke this option. Definition of transport channels is not required for simulating typical one-dimensional branched networks in which each segment discharges only to one downstream segment.

Mass balances

The mass-balance concept is fundamental to reservoir eutrophication modeling. BATHTUB formulates water and nutrient balances by establishing a control volume around each segment and evaluating the following terms:

Inflows	=	Outflows + Increase-in-storage + Net Loss
(External)		(Discharge)
(Advective)		(Advective)
(Diffusive)		(Diffusive)
(Atmospheric)		(Evaporation)

The external, atmospheric, discharge, evaporation, and increase-in-storage terms are calculated directly from information provided by the user in the input file. The remaining are discussed below.

Advective terms reflect net discharge from one segment into another and are derived from water-balance calculations. Diffusive transport terms are applicable only to problems involving simulation of spatial variations within reservoirs. They reflect eddy diffusion (as driven by random currents and wind mixing) and are represented by bulk exchange flows between adjacent segment pairs. Chapra and Reckhow (1983) present examples of lake/embayment models that consider diffusive transport.

As outlined in Table 4.2, five methods are available for estimating diffusive transport rates. Each leads to the calculation of bulk exchange flows which occur in both directions at each segment interface. Dispersion coefficients, calculated from the Fischer et al. (1979) equation (Model 1) or from a fixed longitudinal dispersion coefficient (Model 2), are adjusted to account for effects of numeric dispersion ("artificial" dispersion or mixing that is a consequence of model segmentation). Model 3 can be used for direct input of bulk exchange flows.

Despite its original development based upon data from river systems, the applicability of the Fischer et al. equation for estimating longitudinal dispersion rates in reservoirs has been demonstrated previously (Walker 1985). For a given segment width, mean depth, and outflow, numeric dispersion is proportional to segment length. By selecting segment lengths to keep numeric dispersion rates less than the estimated values, the effects of numeric dispersion on the calculations can be approximately controlled. Based upon Fischer's dispersion equation, the numeric dispersion rate will be less than the calculated dispersion rate if the following condition holds:

$$L < 200W^2Z^{-0.84}$$

where

L = segment length, km

W = mean top width = surface area/length, km

Z = mean depth, m

The above equation can be applied to reservoir-average conditions in order to estimate an upper bound for the appropriate segment length. In most cases, simulated nutrient profiles are relatively insensitive to longitudinal dispersion rates. Fine-tuning of exchange flows can be achieved via the use of segment-specific calibration factors.

While, in theory, the increase-in-storage term should reflect both changes in pool volume and concentration, only the volume change is considered in mass-balance calculations, and concentrations are assumed to be at steady state. The increase-in-storage term is used primarily in verifying the overall water balance. Predictions are more reliable under steady pool levels or when changes in pool volume are small in relation to total inflow and outflow.

Nutrient sedimentation models

For a water balance or conservative substance balance, the net sedimentation term is zero. Nutrient retention submodels are used to estimate net sedimentation of phosphorus or nitrogen in each segment according to the equations specified in Table 4.2. Based upon research results, a second-order decay model is the most generally applicable formulation for representing phosphorus and nitrogen sedimentation in reservoirs:

$$W_s = K_2C^2$$

where,

W_s = nutrient sedimentation rate, mg/m^3-year

K_2 = effective second-order decay rate, m^3/mg-year

C = pool nutrient concentration, mg/m^3

Other options are provided for users interested in testing alternative models (see Table 4.2). The default model error coefficients supplied with the program, however, have been estimated from the model development data set using the second-order sedimentation formulations. Accordingly, error analysis results (predicted coefficients of variation) will be invalid for other formulations (i.e., model codes 3 through 7 for phosphorus or nitrogen), unless the user supplies independent estimates of model error terms.

Effective second-order sedimentation coefficients are on the order of 0.1 m^3/mg-year for total phosphorus and 0.0032 m^3/mg-year for total nitrogen, as specified under "Model 3" in Table 4.2. With these coefficients,

nutrient sedimentation models explain 83 and 84 percent of the between-reservoir variance in average phosphorus and nitrogen concentrations, respectively. Residuals from these models are systematically related to inflow nutrient partitioning (dissolved versus particulate or inorganic versus organic) and to surface overflow rate over the data set range of 4 to 1,000 m/year. Effective rate coefficients tend to be lower in systems with high ortho-P/total P (and high inorganic N/total N) loading ratios or with low overflow rates (4 to 10 m/year). Refinements to the second-order formulations (Models 1 and 2) are designed to account for these dependencies (Walker 1985).

As indicated in Table 4.2, Sedimentation Models 1 and 2 use different schemes to account for effects of inflow nutrient partitioning. In the case of phosphorus, Model 1 performs mass balance calculations on "available P," a weighted sum of ortho-P and nonortho-P which places a heavier emphasis on the ortho-P (more biologically available) component. Model 2 uses total phosphorus concentrations but represents the effective sedimentation rate as inversely related to the tributary ortho-P/total P ratio, so that predicted sedimentation rates are higher in systems dominated by nonortho (particulate or organic) P loadings and lower in systems dominated by ortho-P or dissolved P loadings. The nitrogen models are structured similarly, although nitrogen balances are much less sensitive to inflow nutrient partitioning than are phosphorus balances, probably because inflow nitrogen tends to be less strongly associated with suspended sediments.

Model 1 accounts for inflow nutrient partitioning by adjusting the inflow concentrations, and Model 2 accounts for inflow nutrient partitioning by adjusting the effective sedimentation rate coefficient. While Model 2 seems physically reasonable, Model 1 has advantages in reservoirs with complex loading patterns because a fixed sedimentation coefficient can be used and effects of inflow partitioning are incorporated prior to the mass balance calculations. Because existing data sets do not permit general discrimination between these two approaches, each method should be tested for applicability to a particular case. In most situations, predictions will be relatively insensitive to the particular sedimentation model employed, especially if the ortho-P/total P loading ratio is in a moderate range (roughly 0.25 to 0.60). Additional model application experiences suggest that Method 2 may have an edge over Model 1 in systems with relatively long hydraulic residence times (roughly, exceeding 1 year), although further testing is needed. Because the coefficients are concentration- or load-dependent and because the models do not predict nutrient partitioning in reservoir outflows, Sedimentation Models 2 and 4 cannot be applied to simulations of reservoir networks (Scheme 6 in Figure 4.3).

Based upon error analysis calculations, the models discussed above provide estimates of second-order sedimentation coefficients which are generally accurate to within a factor of 2 for phosphorus and a factor of 3 for nitrogen. In many applications, especially reservoirs with low hydraulic residence times, this level of accuracy is adequate because the nutrient balances are dominated by other terms (especially, inflow and outflow). In applications to existing

reservoirs, sedimentation coefficients estimated from the above models can be adjusted within certain ranges (roughly a factor of 2 for P, factor of 3 for N) to improve agreement between observed and predicted nutrient concentrations. Such "tuning" of sedimentation coefficients should be approached cautiously because differences between observed and predicted nutrient levels may be attributed to factors other than errors in the estimated sedimentation rates, particularly if external loadings and pool concentrations are not at steady state.

Figure 4.4 shows the relationship between hydraulic residence time and mean depth in the reservoirs used in model development. Predictions of nutrient sedimentation rates are less reliable in reservoirs lying outside the data set range. This applies primarily to reservoirs with residence times exceeding 2 years, mean depths greater than 30 m, or overflow rates less than 4 m/year. Tests based upon independent data sets indicate that the sedimentation models are unbiased under these conditions but have higher error variances. In such situations, the modeling exercise should include a sensitivity analysis to model selection and, if possible, calibration of sedimentation coefficients to match observed concentration data. Deviations at the other extremes (reservoirs with lower residence times or higher overflow rates than those represented in the model development data set) are of less concern because the sedimentation term is generally an insignificant portion of the total nutrient budget in such systems (i.e., predicted pool concentrations are highly insensitive to estimated sedimentation rate).

Because the sedimentation models have been empirically calibrated, effects of "internal loading" or phosphorus recycling from bottom sediments are inherently reflected in the model parameter values and error statistics. Generally, internal recycling potential is enhanced in reservoirs with the following characteristics:

a. High concentrations of ortho-phosphorus (or high ortho-P/totalP ratios) in nonpoint-source tributary drainage (indicative of natural sediments that are phosphorus-rich and have high equilibrium phosphorus concentrations).

b. Low summer surface overflow rates, typically < 10 m/year (indicative of low dilution potential for internal loadings generated on a mass per unit area basis and low external sediment loadings).

c. Intermittent periods of stratification and anoxic conditions at the sediment/water interface (contribute to periodic releases of soluble phosphorus from bottom sediments and transport into the mixed layer).

d. Low iron/phosphorus ratios (typically < 3 on a mass basis) in sediment interstitial waters or anaerobic bottom waters (permits migration of phosphorus into aerobic zones without iron phosphate precipitation).

The above conditions are often found in relatively shallow prairie reservoirs; Lake Ashtabula (U.S. Army Engineer District, St. Paul) is an example

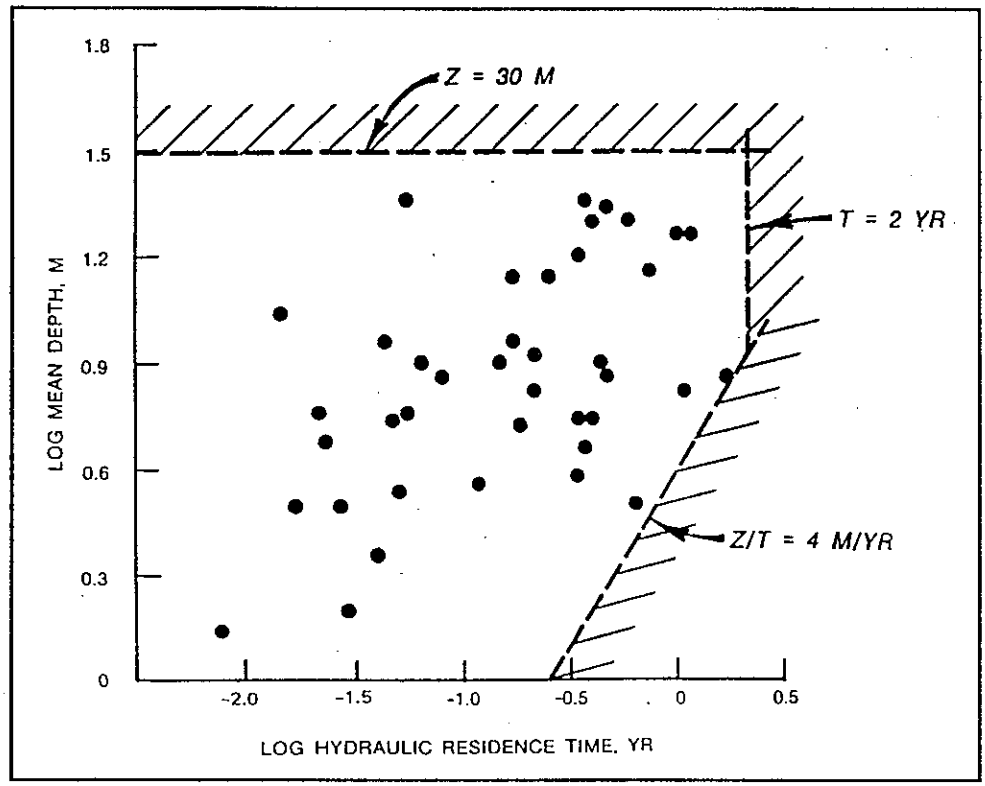


Figure 4.4. Mean depth (Z) versus hydraulic residence time (T) for CE model development data set LOG_{10} scales

included in the CE reservoir data set. In such situations, empirical sedimentation models will underpredict reservoir phosphorus concentrations. Depending upon the efficiency of the internal recycling process, steady-state phosphorus responses can be approximately simulated by reducing the effective sedimentation coefficient (e.g., roughly to 0. in the case of Ashtabula). An option for direct specification of internal loading rates is also provided for use in situations where independent measurements or estimates are available.

Nutrient residence time and turnover ratio

The "averaging period" is defined as the period of time over which water and mass balance calculations are performed. The selection of an appropriate averaging period is an important step in applying this type of model to reservoirs. Two variables must be considered in this process:

$$\text{Mass residence time, year} = \frac{\text{Nutrient mass in reservoir, kg}}{\text{External nutrient loading, kg/year}}$$

$$\text{Turnover ratio} = \frac{\text{Length of averaging period, year}}{\text{Mass residence time, year}}$$

The estimates of reservoir nutrient mass and external loading correspond to the averaging period. The turnover ratio approximates the number of times that the nutrient mass in the reservoir is displaced during the averaging period. Ideally, the turnover ratio should exceed 2.0. If the ratio is too low, then pool and outflow water quality measurements would increasingly reflect loading conditions experienced prior to the start of the averaging period, which would be especially problematical if there were substantial year-to-year variations in loadings.

At extremely high turnover ratios and low nutrient residence times ($\leq$2 weeks), the variability of loading conditions within the averaging period (as attributed to storm events, etc.) would be increasingly reflected in the pool and outflow water quality measurements. In such cases, pool measurement variability may be relatively high, and the biological response (e.g., chlorophyll *a* production) may not be in equilibrium with ambient nutrient levels, particularly immediately following storm events.

Figure 4.5 shows that the hydraulic residence time is an important factor in determining phosphorus and nitrogen residence times, based upon annual mass balances from 40 CE reservoirs used in model development. For a conservative substance, the mass and hydraulic residence times would be equal at steady state. The envelopes in Figure 4.5 show that the spread of nutrient residence times increases with hydraulic residence time; this reflects the increasing importance of sedimentation as a component of the overall nutrient balance. At low hydraulic residence times, there is relatively little opportunity for nutrient sedimentation, and pool nutrient concentrations and residence times can be predicted relatively easily from inflow concentrations. At high hydraulic residence times, predicted pool nutrient concentrations and residence times become increasingly dependent upon the empirical formulations used to represent nutrient sedimentation. This behavior is reflected in the sensitivity curves discussed in Chapter 1.

Normally, the appropriate averaging period for water and mass balance calculations would be 1 year for reservoirs with relatively long nutrient residence times or seasonal (May-September) for reservoirs with relatively short nutrient residence times. As shown in Figure 4.5, most of the reservoirs in the model development data set had phosphorus residence times less than 0.2 year, which corresponds roughly to a nutrient turnover ratio of 2 for a 5-month seasonal averaging period. Thus, assuming that the reservoirs used in model development are representative, seasonal balances would be appropriate for most CE reservoir studies. BATHTUB calculates mass residence times and turnover ratios using observed or predicted pool concentration data. Results can be used to select an appropriate averaging period for each application.

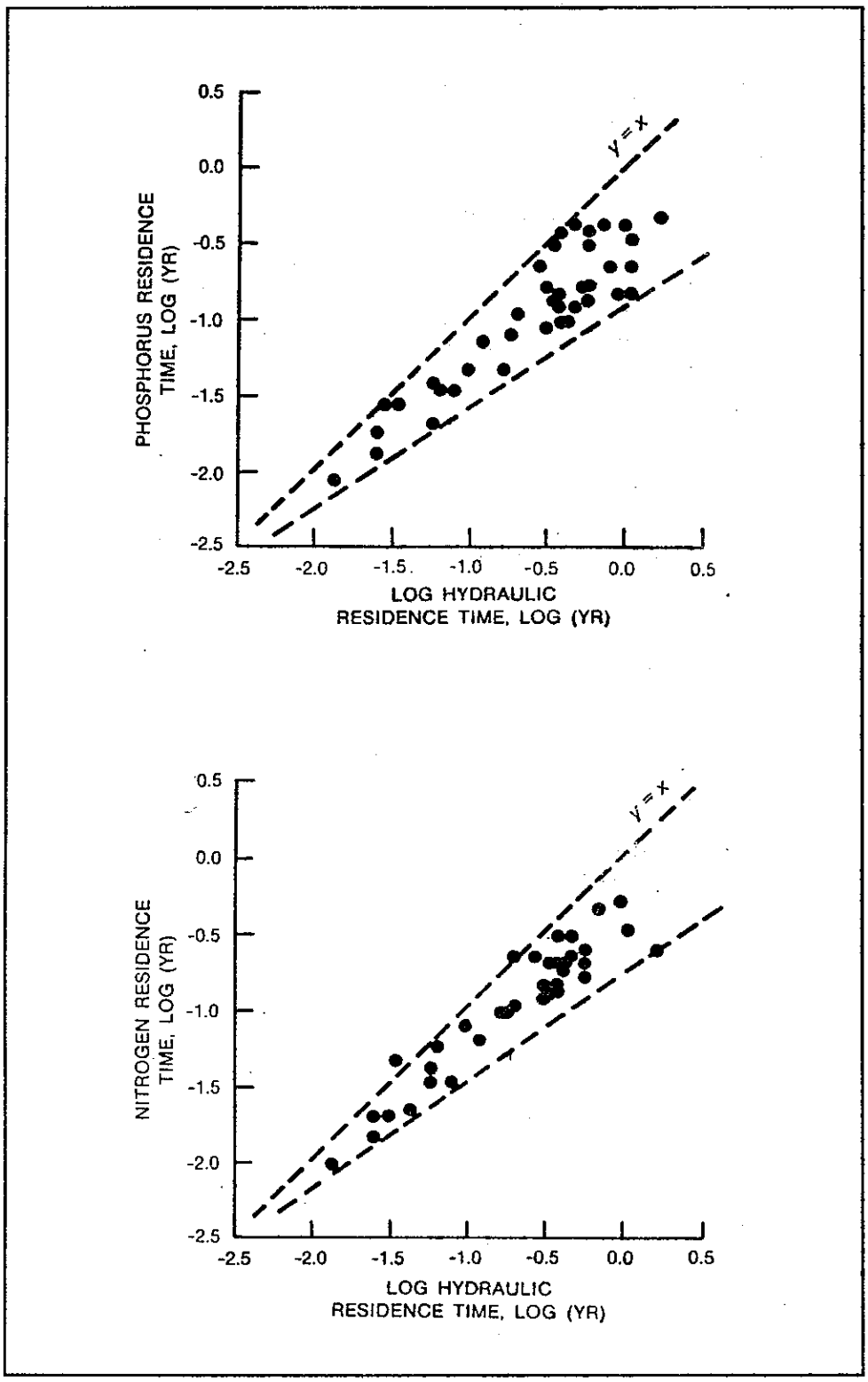


Figure 4.5. Relationships between nutrient residence times and hydraulic residence times in CE model development data set

Solution algorithms

The water balances are expressed as a system of simultaneous linear equations that are solved via matrix inversion to estimate the advective out-flow from each model segment. The mass balances are expressed as a system of simultaneous nonlinear equations which are solved iteratively via Newton's Method (Burden, Faires, and Reynolds 1981). Mass-balance solutions can be obtained for up to three constituents (total phosphorus, total nitrogen, and a user-defined conservative substance). Total phosphorus and total nitrogen concentrations are subsequently input to the model network (Figure 4.2) to estimate eutrophication responses in each segment. Conservative substances (e.g., chloride, conductivity) can be modeled to verify water budgets and calibrate longitudinal dispersion rates.

Eutrophication response models

Eutrophication response models relate observed or predicted pool nutrient levels to measures of algal density and related water quality conditions. Table 4.5 lists diagnostic variables included in BATHTUB output and guidelines for their interpretation. They may be categorized as follows:

a. Basic network variables.

(1) Total P, Total N.

(2) Chlorophyll *a*, Secchi depth.

(3) Organic Nitrogen, Total P - Ortho-P.

(4) Hypolimnetic and Metalimnetic Oxygen Depletion Rates.

b. Principal components of network variables: first and second principal components.

c. Indicators of nitrogen versus phosphorus limitation (Total N-150)/Total P, and Inorganic N/P ratios.

d. Indicators of light limitation.

(1) Nonalgal turbidity, mixed depth x turbidity.

(2) Mixed depth/Secchi depth, and chlorophyll *a* x Secchi Depth.

e. Chlorophyll *a* response to phosphorus: chlorophyll *a*/total P.

f. Algal Nuisance Frequencies.

g. Carlson Trophic State Indices.

Statistical summaries derived from the CE model development data set provide one frame of reference. Low and high ranges given for specific variables provide approximate bases for assessing controlling processes and factors, including growth limitation by light, nitrogen, and phosphorus.

The ranges of conditions under which the empirical models have been developed should be considered in each application. Figure 4.6 depicts relationships among three key variables determining eutrophication responses (total phosphorus, total nitrogen, and nonalgal turbidity) in the CE model development data set. Figure 4.7 depicts relationships among phosphorus, chlorophyll *a*, and transparency. Plotting data from a given application on each of these figures permits comparative assessment of reservoir conditions and evaluations of model applicability. If reservoir data fall outside the clusters in Figure 4.5, 4.6, or 4.7, potential model errors are greater than indicated by the statistics in Table 4.4.

The prediction of mean chlorophyll *a* from observed or predicted nutrient concentrations can be based on one of the five models listed in Table 4.2. Error analyses indicate that it is generally more difficult to predict chlorophyll *a* from nutrient concentrations and other controlling factors than to predict nutrient concentrations from external loadings and morphometry. This partially reflects greater inherent variability of chlorophyll *a*. Chlorophyll *a* models can be described according to limiting factors:

Model	Limiting Factors
1	P, N, light, flushing
2	P, light, flushing
3	P, N
4	P (linear)
5	P (exponential)

Approximate applicability constraints are given in Table 4.2. "Northern lake" eutrophication models are based upon phosphorus/chlorophyll regressions (similar to Models 4 and 5). Research objectives (Walker 1985) have been to define the approximate ranges of conditions under which simple phosphorus/chlorophyll relationships are appropriate and to develop more elaborate models (Models 1-3) which explicitly account for additional controlling factors (nitrogen, light, flushing rate).

While model refinements have been successful in reducing error variance associated with simple phosphorus/chlorophyll relationships by approximately 58 percent, a "penalty" is paid in terms of increased data requirements (e.g., nonalgal turbidity, mixed-layer depths, nitrogen, and flushing rate). For existing reservoirs, these additional data requirements can be satisfied from pool monitoring and nutrient loading information. Otherwise, estimates must be based upon subjective estimates, independent hydrodynamic models, and/or regional data from similar reservoirs. Empirical models for developing independent estimates of turbidity, mixed-layer depth, and mean hypolimnetic

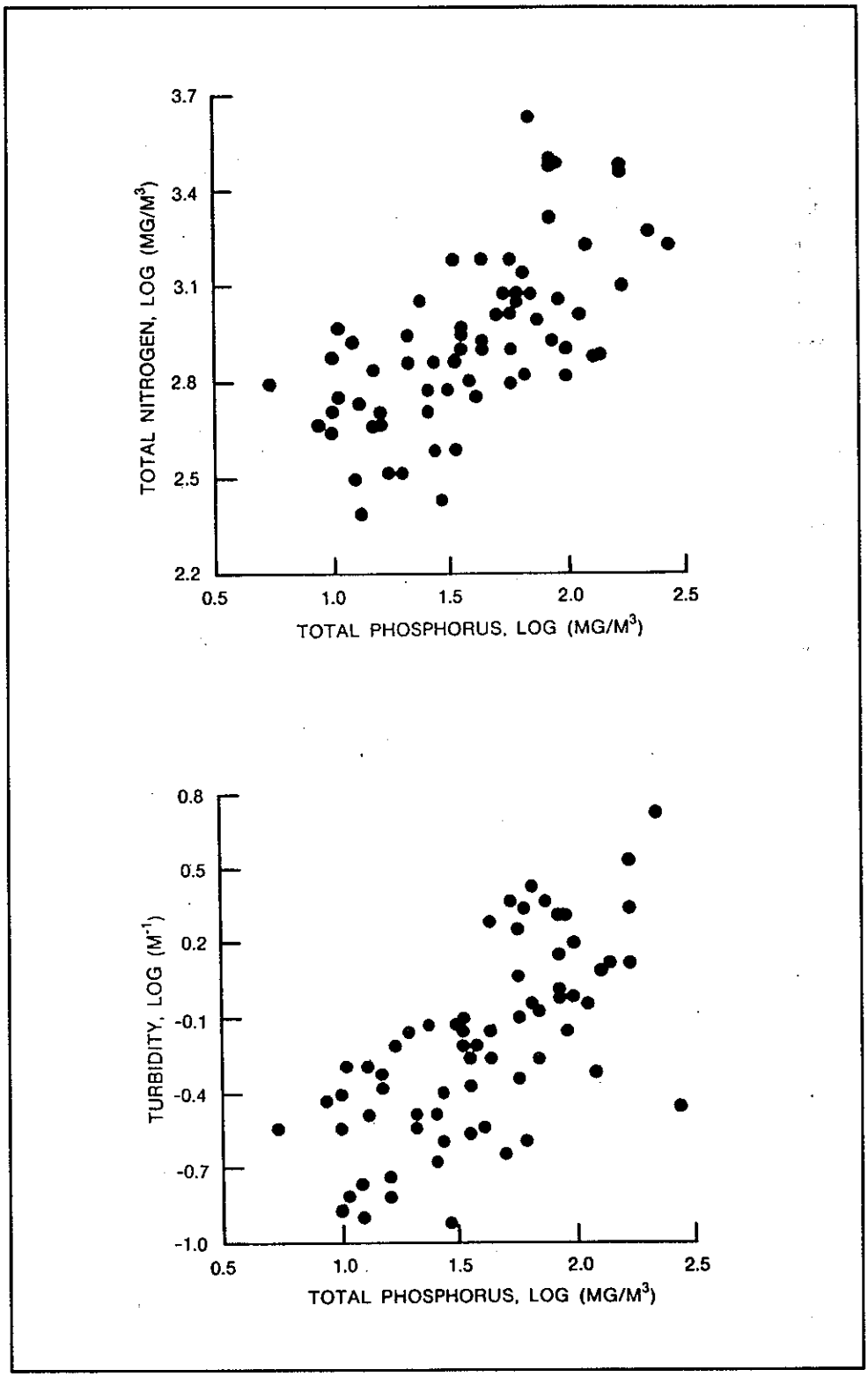


Figure 4.6. Phosphorus, nitrogen, turbidity relationships for CE reservoirs (nonalgal turbidity calculated as 1/Secchi (m) - 0.025 Chl *a* (mg/m^3))

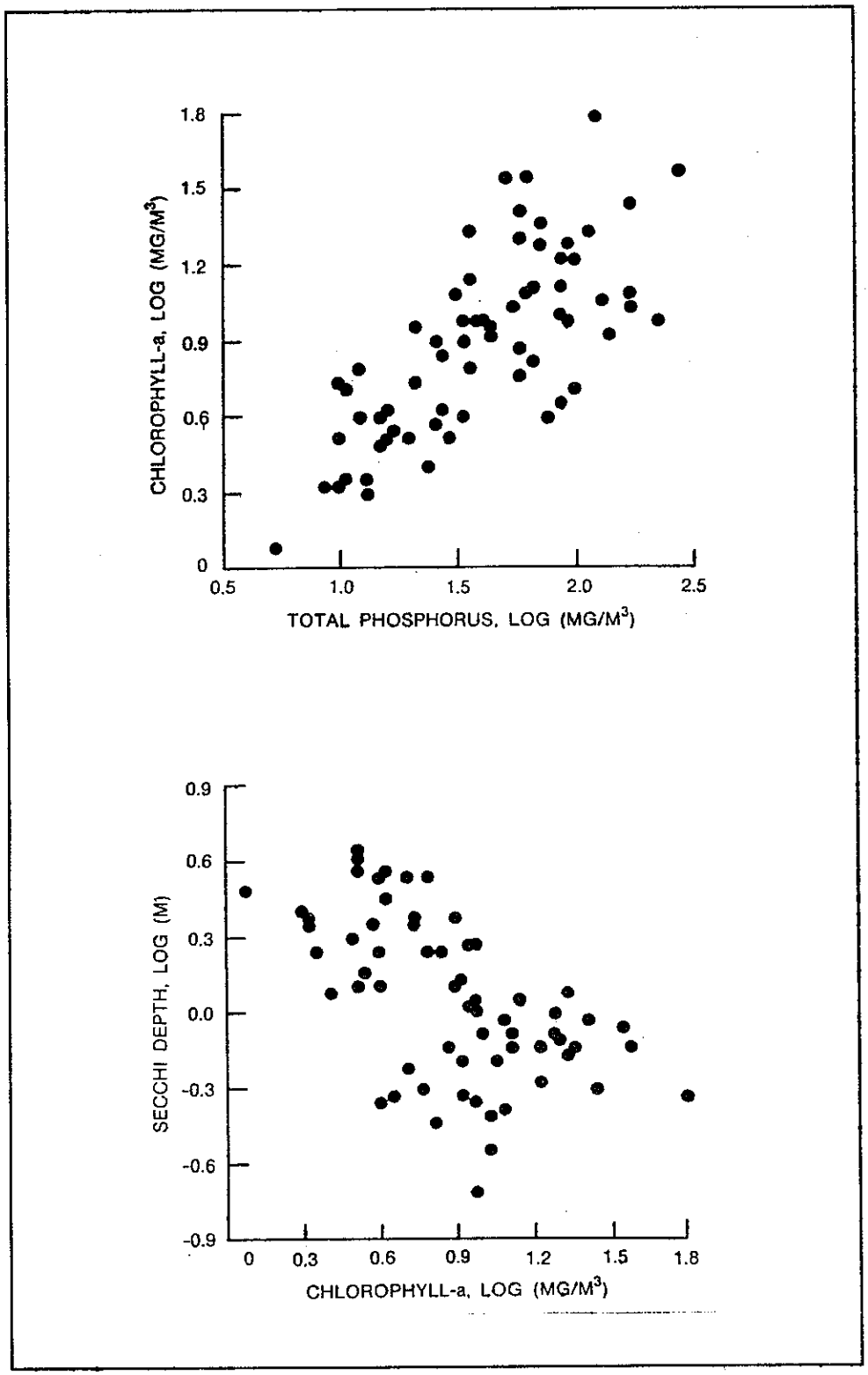


Figure 4.7. Phosphorus, chlorophyll *a*, and transparency relationships for CE reservoirs

depth are summarized in Table 4.6. These should be used only in the absence of site-specific measurements.

Since mechanistic models for predicting nonalgal turbidity levels as a function of deterministic factors (e.g., suspended-solids loadings and the sedimentation process) have not been developed, it is possible to predict chlorophyll *a* responses to changes in nutrient loading in light-limited reservoirs only under stable turbidity conditions. Projections of chlorophyll *a* concentrations should include a sensitivity analysis over a reasonable range of turbidity levels.

Estimates of nonalgal turbidity in each segment (minimum = 0.08 m^{-1}) are required for chlorophyll *a* Models 1 and 2, Secchi Model 1 (Table 4.2), and Nutrient Partitioning Models (Table 4.3). Ideally, turbidity is calculated from observed Secchi and chlorophyll *a* data in each segment. If the turbidity input field is left blank, the program calculates turbidity values automatically from observed chlorophyll *a* and Secchi values (if specified). An error message is printed, and program execution is terminated if all of the following conditions hold:

a. Turbidity value missing or zero.

b. Observed Chlorophyll *a* or Secchi missing or zero.

c. Chlorophyll *a* Models 1, 2 or Secchi Model 1 used.

In the absence of direct turbidity measurements, the multivariate regression equation specified in Table 4.6 can be used (outside of the program) to estimate a reservoir-average value. Such estimates can be modified to based upon regional databases.

Model calibration and testing have been based primarily upon data sets describing reservoir-average conditions (Walker 1985). Of the above options, Model 4 (linear phosphorus/chlorophyll *a* relationship) has been most extensively tested for use in predicting spatial variations within reservoirs. The chlorophyll/phosphorus ratio is systematically related to measures of light limitation, including the chlorophyll *a* and transparency product, and the product of mixed-layer depth and turbidity. If nitrogen is not limiting, then light-limitation effects may be approximately considered by calibrating the chlorophyll/ phosphorus ratio to field data; this is an alternative to using the direct models (i.e., Models 1 and 2) that require estimates of turbidity and mixed-layer depth in each segment. The relationships depicted in Figure 4.8 may be used to obtain approximate estimates of reservoir-average calibration coefficients for use in Model 4 based upon observed monitoring data or independent estimates of turbidity and mixed-layer depth (Table 4.6).

Models 1 and 3 attempt to account for the effects of nitrogen limitation on chlorophyll *a* levels. Nitrogen concentrations are predicted from the external nitrogen budget and do not account for potential fixation of atmospheric nitrogen by bluegreen algae. Nitrogen fixation may be important in some

Table 4.6
Equations for Estimating Nonalgal Turbidity, Mixed Depth, and Hypolimnetic Depths in Absence of Direct Measurements

Nonalgal turbidity

Based upon measured chlorophyll *a* and Secchi depth:

$$a = 1/S - 0.025\ B \text{ (minimum value } = 0.08\ 1/m)$$

where

S = Secchi depth, m

B = chlorophyll *a*, mg/m^3

Multivariate turbidity model:

$$\log(a) = 0.23 - 0.28 \log(Z) + 0.20 \log(FS) + 0.36 \log(P) - 0.027\ LAT + 0.35\ du \quad (R^2 = 0.75,\ SE^2 = 0.037)$$

where

LAT = dam latitude, deg N

du = regional dummy variable, (1 for U.S. Army Engineer (USAE) Divisions North Pacific, South Pacific, Missouri River, and Southwest (except USAE District, Little Rock) and USAE District, Vicksburg, and 0 for other locations)

F_s = summer flushing rate ($year^{-1}$) or 0.2, whichever is greater

Z = mean total depth, m

P = total phosphorus concentration, mg/m^3

Mean depth of mixed layer (entire reservoir, for Z < 40 m)

$$\log(Zmix) = -0.06 + 1.36 \log(Z) - 0.47\ [\log(Z)]^2 \quad (R^2 = 0.93,\ SE^2 = 0.0026)$$

Mean depth of hypolimnion (entire reservoir)

$$\log(Zh) = -0.58 + 0.57 \log(Zx) + 0.50 \log(Z) \quad (R^2 = 0.85,\ SE^2 = 0.0076)$$

impoundments, as indicated by the presence of algal types known to fix nitrogen, low N/P ratios, and/or negative retention coefficients for total nitrogen (Outflow N > Inflow N). In such situations, nitrogen could be viewed more as a trophic response variable (controlled by biologic response) than as a causal factor related directly to external nitrogen loads. Use of Models 1 and 3 may be inappropriate in these cases; modeling of nitrogen budgets would be useful for descriptive purposes, but not useful (or necessary) for predicting chlorophyll *a* levels.

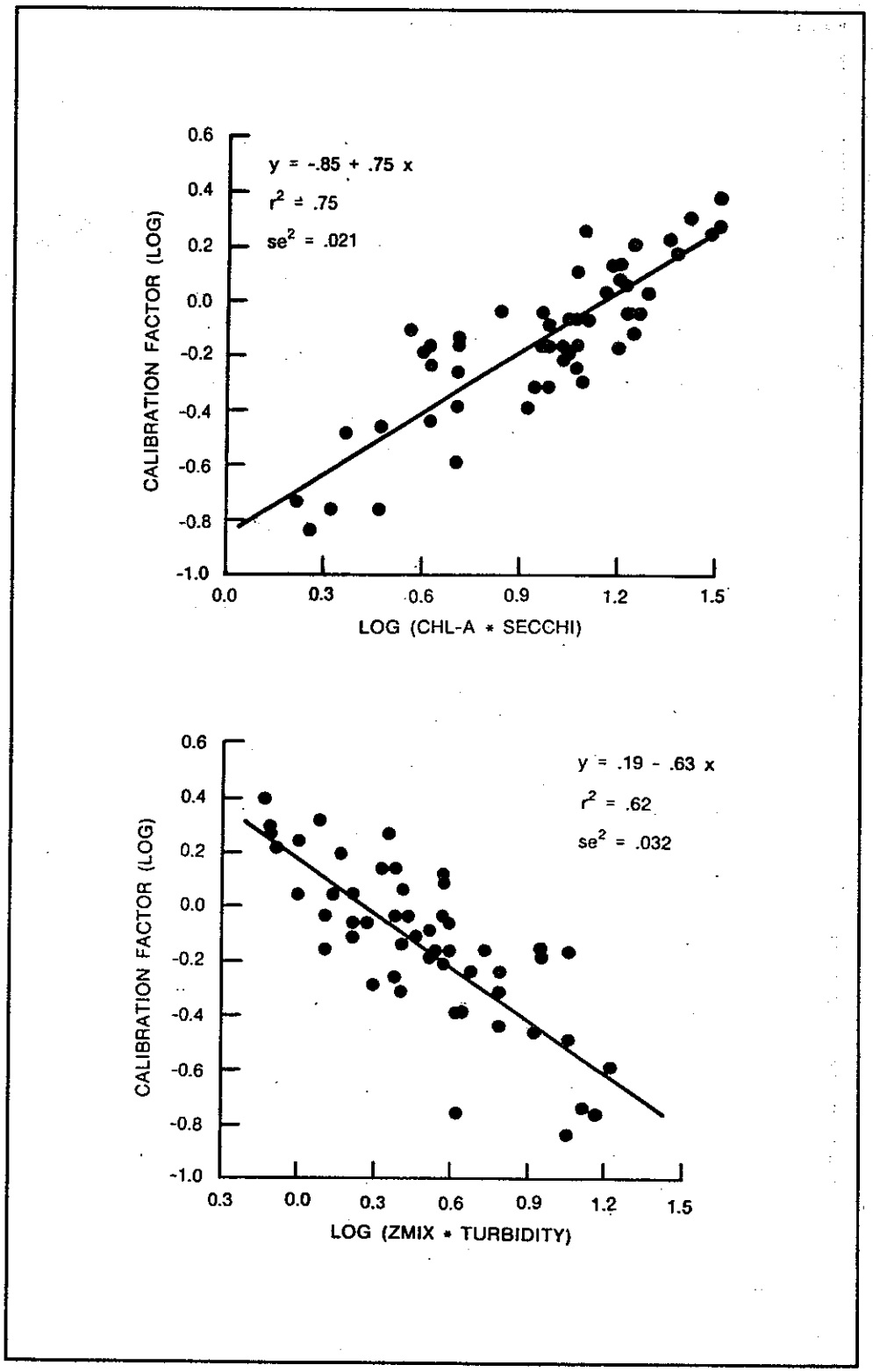


Figure 4.8. Calibration factor for linear phosphorus/chlorophyll model versus light limitation factors

If the reservoir is stratified and oxygen depletion calculations are desired, temperature profile data taken from the period of depletion measurements (typically late spring to early summer) are used to estimate the mean depth of the hypolimnion. If mean hypolimnetic depth is not specified (=0.0), the reservoir is assumed to be unstratified and oxygen depletion calculations are bypassed. The oxygen depletion models are based upon data from near-dam stations. Accordingly, mean hypolimnetic depths should be specified only for near-dam segments, based upon the morphometry of the entire reservoir (not the individual segment). In modeling collections or networks of reservoirs (Schemes 5 and 6 in Figure 4.3), a mean hypolimnetic depth can be specified separately for each segment (i.e., each reservoir). Table 4.6 gives an empirical relationship that can be used to estimate mean hypolimnetic depth in the absence of direct measurements.

Calibration factors

The empirical models implemented in BATHTUB are generalizations about reservoir behavior. When applied to data from a particular reservoir, observations may differ from predictions by a factor of two or more. Such differences reflect data limitations (measurement or estimation errors in the average inflow and outflow concentrations), as well as unique features of the particular reservoir. A facility to calibrate the model to match observed reservoir conditions is provided in BATHTUB. This is accomplished by application of 'Calibration Factors', which modify reservoir responses predicted by the empirical models, nutrient sedimentation rates, chlorophyll *a* concentrations, Secchi depths, oxygen depletion rates, and dispersion coefficients. The calibrated model can be applied subsequently to predict changes in reservoir conditions likely to result from specific management scenarios under the assumption that the calibration factors remain constant.

For convenience, calibration factors can be applied on two spatial scales: global (applying to all segments) and individual (applying to each segment). The product of the global and individual calibration factors is multiplied by the reservoir response predicted by the empirical model to produce the "calibrated" prediction. All calibration factors have a default value of 1.0. Separate sets of calibration factors can be applied to any or all the following response predictions:

Nutrient Sedimentation Rates (or Concentrations)
Chlorophyll *a* Concentrations
Secchi Depths
Longitudinal Dispersion Rates
Oxygen Depletion Rates

Recognizing that differences between observed and predicted responses are at least partially due to measurement errors, calibration factors should be used very conservatively. Program output includes statistical tests to assist the user

in assessing whether calibration is appropriate. General guidance is presented in a subsequent section (see Application Steps).

Error analysis

The first-order error analysis procedure implemented by BATHTUB can be used to estimate the uncertainty in model predictions derived from uncertainty in model inputs and uncertainty inherent in the empirical models. To express uncertainty in inputs, key input variables are specified using two quantities:

Mean = Best Estimate

CV = Standard Error of Mean/Mean

The CV reflects the uncertainty in the input value, expressed as a fraction of the mean or best estimate. CV values can be specified for most input categories, including atmospheric fluxes (rainfall, evaporation, nutrient loads), tributary flows and inflow concentrations, dispersion rates, and observed reservoir quality. FLUX and PROFILE can be used to estimate Mean and CV values for inflow and reservoir concentrations, respectively. Model uncertainty is considered by specifying a CV value for each global calibration factor; default CV values derived from CE reservoir data sets are supplied (see Table 4.4). Error-analysis calculations provide only rough indications of output uncertainty. Four error analysis options are provided:

None
Inputs (Consider input uncertainty only)
Model (Consider model uncertainty only)
All (Consider input and model uncertainty)

Specified CV values are not used in the calculations if error analyses are not requested.

Program Operation

Introduction

This section summarizes procedures for running the BATHTUB program. When the program is run (from the DOS prompt), a series of help screens summarizing model features is first encountered. These are followed by a menu that provides interactive access to seven types of procedures with the following functions:

```
B A T H T U B  -  VERSION 5.3
Case    Run    List    Plot    Utilities    Help    Quit

Case     Define Case - Read, Enter, Edit, or List Input Values
List     List Model Output
Run      Check Input Values & Run Model
Help     View Supplementary Help Screens
Quit     End Current Session
```

A procedure category is selected by moving the cursor (using arrow keys) or by pressing the first letter of the procedure name. Assistance in navigating around the menu can be obtained by pressing the **<F7>** function key. Generally, **Case**, **Run**, **List**, and **Plot** procedures would be implemented sequentially in a given session. Program control returns to the top of the menu after executing a procedure. A **Help** screen describing the selected procedure can be viewed by pressing **<F1>**.

Case procedures

Case procedures are invoked to define, edit, save, retrieve, or list input values. Once **Case** is selected, the menu expands by one line to show further choices. The following procedure categories are available:

```
B A T H T U B  -  VERSION 5.3
Case    Run    List    Plot    Utilities    Help    Quit
Edit    Models    Read    Save    New    Change    List    Morpho

Edit          Edit Case Data
Models        Set Model Options
Read          Read Case Data File
Save          Save Case Input Data File
New           Reset Input Values & Start New Case
Change        Delete, Insert, or Copy Segments or Tributaries
List          List Current Case Input Values
Morpho        List Segment Morphometry
```

Entry and editing of data is accomplished by selecting **Edit**, which provides access to data-entry screens in the following categories:

```
B A T H T U B  -  VERSION 5.3
Case    Run    List    Plot    Utilities    Help    Quit
Edit    Models    Read    Save    New    List    Morpho
Dimensions  Globals  Segments  Tribs  Nonpoint  Mcoefs  Channels  All

Dimensions    Edit Case Dimensions, File Name, Title, User Notes
Globals       Edit Global Parameters, Precip., Evap., Atmos. Loads
Segments      Edit Segment Data
Tribs         Edit Tributary and Point-Source Data
Nonpoint      Edit Nonpoint Landuse Categories & Export Coefficients
Mcoefs        Edit Default Model Coefficients & Error Terms
Channels      Edit Transport Channels
All           Edit All Input Data Groups
```

Each of the above procedures provides access to a different data-entry screen. These are listed along with their associated **Help** screens below:

Once the case input values have been entered, the **Case/Models** procedure can be used to define model options in the following categories:

```
B A T H T U B  -  VERSION 5.3
Case      Run      List      Plot      Utilities      Help      Quit
Edit      Models      Read      Save      New      List      Morpho

Model Categories:

   Conservative Substance Balance
   Phosphorus Sedimentation Model
   Nitrogen Sedimentation Model
   Chlorophyll a Model
   Secchi Model
   Dispersion Model
   Phosphorus Calibration Method
   Nitrogen Calibration Method
   Nutrient Availability Factors
   Mass-Balance Calculation Method
```

Subsequent menus are presented that allow the user to set model options in any of the above categories. Option settings are documented in Table 4.2. For most options, a setting of zero will bypass the corresponding calculations. Conservative substance (e.g., chloride) balances may be useful for verifying water balances and calibrating diffusive transport coefficients. For the phosphorus, nitrogen, and chlorophyll models, settings of 1 or 2 correspond to the most general formulations identified in model testing. If the conservative substance, phosphorus, or nitrogen sedimentation model is set to 0, corresponding mass balance calculations are bypassed, and predicted concentrations are set equal to observed values in each segment. This feature is useful for assessing pool nutrient/chlorophyll relationships and controlling factors in the absence of nutrient loading information.

The **Case/Read** procedure is used to read existing data sets and has two choices beneath it:

```
B A T H T U B  -  VERSION 5.3
Case      Run      List      Plot      Utilities      Help      Quit
Edit      Models      Read      Save      New      List      Morpho
Data      Translate

Data          Read Version 5.3 Data set
Translate     Read Data Set Created with Previous Versions of Program
```

Case input data can be saved (along with selected model options) on disk (**Case/Save**) for retrieval in subsequent sessions (**Case/Retrieve**). Case files should be named with an extension of '.BIN' to facilitate future identification and retrieval. The **Case/Save** procedure saves the current data set. The **Case/New** procedure resets all data and model coefficients to their default values and begins a new data set. The **Case/List** procedure lists all input values for the current case. The **Case/Morpho** option lists a brief summary of segment morphometric features.

Run procedures

Once a complete set of input values have been entered and saved on disk, the model can be run using the following procedures:

```
B A T H T U B  -  VERSION 5.3
Case      Run      List      Plot      Utilities      Help      Quit
Model     Sensitivity
NoError   Inputs   Model  All
```

```
NoError  Run Model Without Error Analysis
Inputs         Error Analysis -  Case Input Variables Only
Model          Error Analysis - Model Error Terms & Calib Factors
All                  Error Analysis - All Input Variables and Model Parameters
```

The first procedure (**Run/Model/NoError**) is suggested for trial runs of newly entered cases. The program first checks for valid input data and lists any errors identified. Error messages describe the error type and often refer to a particular segment or tributary number. If an error is encountered, execution stops and control is returned to the main menu. The user would then access **Case** procedures to identify and correct the invalid input data. If the number of error messages encountered fills up more than one screen, a copy of the error messages is saved in a disk file which can be accessed using the **Utilities/Error** procedure.

If no input errors are detected, the program attempts to solve the mass-balance equations. In rare cases, solutions cannot be reached and an error message appears. This type of problem may occur when the segmentation scheme is not defined correctly (outflow segment numbers are not correctly specified) or when the solution of the water-balance equation indicates that there is no net outflow from the reservoir (evaporation and/or withdrawals exceed inflows). Steady-state solutions cannot be reached in such situations.

If a solution is reached, control is returned to the main menu. The message 'MODEL EXECUTED' appears in the lower right hand corner of the screen. This indicates that **List** and **Plot** procedures can be accessed to review output. If input values are subsequently edited or a new data file is read, the model must be executed again before output can be viewed. As indicated above, the **Run/Model** procedures can be implemented with four levels of error analysis. **Error analysis** procedures require longer execution times because the model must be solved many times to test sensitivity to each input variable and/or model error term.

The **Run/Sensitivity** procedures test the sensitivity of predicted nutrient concentrations in each segment to variations in nutrient sedimentation rate and in longitudinal dispersion rate:

```
B A T H T U B  -  VERSION 5.3
Case      Run      List      Plot      Utilities      Help      Quit
Model     Sensitivity
Conserv     Total P         Total N
```

```
Conserv  Run Sensitivity Analysis for Conservative Substance
Total P  Run Sensitivity Analysis for Total Phosphorus
Total N  Run Sensitivity Analysis for Total Nitrogen
```

List procedures

Several tabular formats are provided to summarize and highlight various aspects of the model output. These are accessed by selecting **List** from the main menu:

```
B A T H T U B  -  VERSION 5.3
Case      Run      List     Plot     Utilities     Help     Quit
Hydraul   Balances  Compar  Diagnos  Profiles   Flownet   Table  Short
```

```
Hydraul          List Morphometry/Hydraulics/Dispersion Table
Balances/        List Water and Mass Balances
  Gross          Gross Water and Mass Balances - All Segments
  By Segment     Water and Mass Balances by Segment - Detailed
  Summary        Water and Mass Balances by Segment - Summary
Compar           Compare Observed & Predicted Values
Diagnos          List Observed & Predicted Diagnostic Variables
Profiles         List Summary of Predicted Values
Flownet          List Flow Network Summary
Table            List Table of Predicted Values for Selected Variables
Short            Short Table of All Predicted Values by Segment
```

Each procedure writes results to a temporary disk file. When output is complete, a utility is executed to permit interactive viewing of the output file. Cursor keys can be used to move forward or backward though the file. Results can be copied to a permanent disk file by pressing the **<F8>** function key. A **Help** screen describing the current output format can be accessed by pressing the **<F1>** function key. Examples and explanation of each output format are given in the 'Sample Output' section.

Plot procedures

Graphs of observed and predicted concentrations can be viewed by accessing the **Plot** procedures:

```
B A T H T U B  -  VERSION 5.3
Case      Run      List     Plot     Utilities     Help     Quit
Nutrients  All     Some    Define
```

```
Nutrients        Plot Total Phosphorus & Total Nitrogen Only
All              Plot All Variables
Some             Plot Selected Variable(s)
Define/          Edit Plot Scale Options (Default, Linear, or Logarithmic)
  1Default       Use Default Scale Types
  2Linear        Use Linear Scales for All Variables
  3Log           Use Logarithmic Scales for All Variables
```

After specifying one of these procedures, plot formats can be selected from subsequent menu screens:

1. Observed and Predicted vs. Model Segment
2. Observed vs. Predicted
3. Observed/Predicted Ratio vs. Model Segment

If error analysis calculations have been performed, Format 1 shows predicted concentrations ± 1 standard error. Similarly, observed concentrations are shown ± 1 standard error for observed variables with specified CV values. The last model segment displayed in Formats 1 and 3 shows results for the area-weighted mean across all case segments; for example, if the case contains 4 segments, area-weighted means will be shown above segment number 5. Samples of each plot format are given in the 'Sample Output' section.

Utility procedures

Program utilities can be accessed from the main menu to provide the following functions:

```
B A T H T U B  -  VERSION 5.3
Case     Run     List     Plot     Utilities     Help     Quit
Output   Restrict   View  Error
Screen   File
```

```
Output/        Set Output Destination - Screen or File
  Screen       Direct Output to Screen (Default)
  File         Direct Output to Disk File
Restrict       Restrict Output & Plots to Specific Segment(s)
View           View any DOS Text File
Error          View Error Message File
```

Output can be redirected from the screen to a disk file. If **Utilities/Output/File** is selected, all output listings will be routed to a user-specified disk file; no screen output will occur until **Utilities/Output/Screen** is selected. This utility is useful for creating permanent log files of program output for future reference or for inclusion in reports. The **Utilities/Restrict** procedure can be used to restrict program output (listing and plots) to specific segments. As discussed above, the **Utilities/Error** procedure permits viewing of any error messages from the last execution of the model. This is useful for debugging input files.

Help procedure

Supplementary help screens can be viewed from the program menu by selecting the **Help**:

```
B A T H T U B  -  VERSION 5.3
Case     Run     List     Plot     Utilities     Help     Quit
```

This provides access to help screens that are organized in the following general categories:

```
Introductory Screens
Input Topics
Model Variables and Options
Output Topics
Program Operation
```

Context-sensitive help screens can also be accessed during execution of other procedures by pressing the **<F1>** function key.

Quit procedure

```
B A T H T U B  -  VERSION 5.3
Case    Run    List    Plot    Utilities    Help    Quit
```

Selecting **Quit** from the main menu ends the current session, after checking whether this is the user's intention. The current case file should be saved before quitting.

Application Steps

This section describes basic steps involved in applying BATHTUB to a reservoir. Three application scenarios can be defined, based upon reservoir status and data availability:

		Data Availability	
Scenario	Reservoir	Water/Nutrient Balance Data	Pool Water Quality Data
A	Existing	Yes	Yes
B	Existing	No	Yes
C	Existing or Proposed	Yes	No

Scenario A normally applies to an existing reservoir with nutrient balance data and pool water quality data. Under Scenario B, nutrient balance (loading) information is lacking; in this case, the program can be used for diagnostic purposes (e.g., assessing pool nutrient/chlorophyll relationships and regional ranking). Scenario C is distinguished by lack of pool water quality data, which would otherwise be used for preliminary testing and calibration.

For each scenario, application procedures can be summarized in terms of the following basic steps:

Step	Description
1	Watershed Data Reduction
2	Reservoir Data Reduction
3	Data Entry and Verification
4	Water Balances
5	Nutrient Turnover

6	Diffusive Transport
7	Nutrient Balances
8	Chlorophyll *a* and Secchi
9	Verification
10	Diagnostics
11	Predictions

These steps are designed to be executed sequentially. Reiteration of previous steps is common in typical modeling projects. As described below, not all modeling steps are applicable to each scenario. The procedures are intended to provide general indications of factors to be considered during the modeling process. They are not intended as a rigid framework for applying the model. User judgment must be exercised to account for unique aspects of each application. The Theory section of this chapter describes model formulations, options, and other background information required to support applications. Before considering each scenario, a few general aspects of developing model applications are discussed.

It is important to define purpose and scope prior to undertaking the modeling effort. This includes specifying management issues to be evaluated and types of model output required to support the evaluations. In typical applications, most of the effort and cost is devoted to data collection and data reduction. In situations where modeling is undertaken after the monitoring data have been acquired, model results may be severely limited by data. This situation can be avoided by initiating modeling before designing and undertaking additional monitoring. Modeling can be conducted in two phases. The first phase is based upon historical data and helps to define data gaps that can be filled in subsequent monitoring. The second phase is based upon more complete data. Chapter 1 contains guidance for designing monitoring programs to support model applications.

In defining study scope, the user must decide which components will be modeled. In the most general case, a model application involves specification of tributary loads (flows and concentrations) for a conservative tracer, total phosphorus, ortho phosphorus, total nitrogen, and inorganic nitrogen. Of these, only total phosphorus is absolutely necessary. Based upon the CE reservoir data set used in developing the phosphorus sedimentation models, additional consideration of ortho phosphorus loads reduces the standard error of predicted reservoir-mean phosphorus concentrations by 16 to 32 percent, depending upon model formulation. Considering total phosphorus loads only will provide unbiased predictions of reservoir response, however, if the ratio of tributary ortho phosphorus load to tributary total phosphorus load is in the range of 15 to 50 percent. Considering nitrogen loads provides additional descriptive information, but may not contribute significantly to predicting the trophic response of the reservoir, as measured by chlorophyll *a* because nitrogen may not be limiting algal growth or because external nitrogen loads may be supplemented by fixation of atmospheric nitrogen (see Eutrophication

response models). Modeling a conservative tracer, such as chloride or conductivity, provides a means for calibrating and testing diffusive transport terms and for testing overall water balances.

BATHTUB provides a facility for calibrating the empirical models to account for site-specific conditions (see Calibration factors). Calibration should be attempted only by experienced users working with intensive monitoring data sets. A potential need for site-specific calibration is indicated when significant differences between observed and predicted concentrations are found during initial model runs. A conservative approach to calibration is recommended (adjusting the fewest number of coefficients within reasonable ranges). Differences between observed and predicted concentrations result from two basic sources: data errors and model errors. Random data errors always occur in the specification of model input values (tributary loads, observed reservoir water quality, flows, morphometry, etc.). Omission of important nutrient sources in formulating the reservoir nutrient balance is another type of random error. These are essentially artifacts of study design, data collection, and data reduction. Model errors reflect true differences between model predictions and reservoir response. Calibration to account for model errors may be justified, but calibration to account for data errors is generally not justified. One possible exception to this rule occurs when data errors are not random, but are biases attributed to differences in measurement methods; for example, calibration of the chlorophyll *a* model may be appropriate to account for differences in measurement technique. BATHTUB error analyses can help to distinguish between model and data errors. Calibration is generally not necessary when there is considerable overlap between observed and predicted distributions (**Plot** procedures).

Each application should start with construction of a schematic diagram showing major reservoir regions, inflow streams, point sources, outflow streams, and monitoring stations. Examples of schematic diagrams are given in the Documented Session and Instructional Cases sections at the end of this chapter. The diagram can be overlaid on a reservoir map. Initial definitions of model segments should be shown; these may be revised based upon subsequent review and summary of monitoring data. Segments and tributaries should be labeled and numbered. The diagram provides a useful frame of reference for subsequent data reduction and modeling steps.

Scenario A - Existing reservoir with loading and pool water quality data

Step 1 involves reduction of watershed data used in modeling. Formulation of a drainage area "balance" is an important first step in summarizing watershed characteristics. The FLUX program (Chapter 2) can be used for estimating seasonal and/or annual loadings for gauged tributaries, point sources, and discharges. An averaging period for calculating tributary inflows must be selected. This is typically 1 year for reservoirs with relatively long hydraulic residence times and one growing season (April-September or

May-September) for reservoirs with relatively short residence times (see Nutrient residence time and turnover ratio). Sensitivity to choice of averaging period can be tested by creating separate input files for different averaging periods.

Ungauged inflows and stream concentrations can be estimated by drainage-area proportioning using data from other regional watersheds with similar land uses. Alternatively, ungauged inflows and concentrations can be estimated by calibrating and applying the nonpoint source model provided with BATHTUB (TYPE=2 tributaries). Calibration requires specification of typical runoff rates and concentrations as a function of land use (**Case/Edit/Non-Point** Procedure).

Step 2 involves reduction of reservoir morphometric and water quality data. Morphometric information can be estimated from contour maps and/or sediment accumulation surveys. PROFILE (Chapter 3) can be used to summarize observed water quality conditions by segment and calculate oxygen depletion rates in stratified reservoirs. Segment boundaries depicted on the schematic diagram may be revised based upon review of pool monitoring data. Generally, it is appropriate to aggregate adjacent reservoir areas with similar water quality into a single segment. Box plots summarizing water quality data by station can be useful for this purpose (see PROFILE, Chapter 3). Even if significant spatial variations in water quality are apparent, division of the reservoir into multiple segments is not necessary for modeling. Modeling the entire reservoir with one segment provides predictions of area-weighted mean concentrations, which may be adequate to support management decisions. In such situations, it will be particularly important to apply spatial weighting factors when averaging observed water quality data. Defining multiple segments may be required to support management decisions. Simulating spatial variations within the reservoir can provide evidence of model applicability and reliability that is not available in single-segment applications.

In Step 3, an input data file is created by running the **Case/Edit** procedures (see Data-Entry Screens). The input file should be listed and checked for data-entry errors and completeness. Default model options should be modified to reflect the components being modeled (conservative substance, phosphorus, nitrogen). If ortho phosphorus and/or inorganic nitrogen concentrations for all stream inflows are not supplied, availability factors should not be used in calculating nutrient balances. This is achieved by setting the 'Availability Factor' option to 0 using the **Case/Models** procedure.

Water balances are checked and adjusted in Step 4 using the **List/ Balances/Gross** procedure. Measured flows for all major inflow and outflow streams must be specified in order to check the water balance. It may be appropriate to adjust certain inflow, outflow, and/or increase-in-storage terms until balances are established. The appropriate terms to adjust vary from case to case, depending upon watershed characteristics and flow monitoring networks. Based upon familiarity with the flow data sources, the user should assess the most likely source(s) of water balance error and adjust the

appropriate value(s) in the CASE file. Flow-balance errors are often attributed to ungauged surface or groundwater inflows. If a water balance cannot be established with reasonable adjustments, additional monitoring with refinements to flow gauging networks may be required.

Nutrient turnover ratios are checked in Step 5 using the **List/Balances/Gross** procedure. As discussed above (see Nutrient residence time and turnover ratio), the appropriate averaging period for mass-balance calculations is determined by the observed turnover ratio of the limiting nutrient (usually phosphorus). A seasonal averaging period (April/May through September) is usually appropriate if it results in a turnover ratio exceeding 2.0. An annual averaging period may be used otherwise. The turnover ratio criterion is an approximate guideline, which may be adjusted from case to case. Other considerations (such as comparisons of observed and predicted nutrient levels) can also be used as a basis for selecting an appropriate averaging period, particularly if the turnover ratio is near 2.0. Note that if the reservoir is vertically stratified and significant hypolimnetic accumulations of phosphorus occur, seasonal phosphorus turnover ratios calculated from mixed-layer concentrations will be overestimated. In this situation, mixed-layer nutrient levels during the growing season may reflect nutrient transport from the bottom waters via diffusion or mixing processes, as compared with nutrient inputs from external sources. Both annual and seasonal balances should be tested in this situation. Depending upon results of Step 5, it may be necessary to repeat the calculation of tributary loadings (Step 1) using a different averaging period.

Step 6 involves checking and possible calibration of diffusive transport terms using the **List/Hydrau** procedure. If numeric dispersion exceeds the estimated dispersion in a given segment, the user should consider revising the segmentation scheme (e.g., increasing segment numbers and thus decreasing segment lengths) until this criterion is satisfied. In some cases, this may be difficult to achieve with a reasonable number of segments, particularly in upper-pool segments, where advective velocities tend to be greater. The criterion may be waived if the sensitivity of predicted nutrient profiles to alternative segmentation schemes is shown to be minimal.

Conservative tracer data (typically chloride or conductivity), may be used to calibrate diffusive transport terms in problems involving more than one segment. An overall tracer mass balance should be established (**List/Balances**) prior to calibrating transport terms. Calibration involves adjusting the global calibration factor for dispersion (**Case/Edit/Mcoefs**) and/or segment calibration factors (**Case/Edit/Segments**) to match observed tracer profiles. Generally, predicted concentration gradients will decrease with increasing dispersion rates. The **Run/Model/Sensitivity** procedure shows the sensitivity of predicted tracer concentrations to fourfold variations in dispersion rates. Where possible, adjustments should be made only to the global calibration factor (keeping segment calibration factors at their default setting of 1.0); this is a more conservative calibration approach than adjusting values for each segment individually. For Dispersion Model 1, the global calibration factor should be in the range of 0.25 to 4.0, the approximate 95-percent confidence limit for

dispersion estimated from Fischer's equation. If adjustment outside this range is required, other dispersion models and/or alternative segmentation schemes should be investigated.

If there is a long wind fetch and segments are aligned along predominant wind directions, upward adjustment of the dispersion factors may be necessary. Conversely, downward adjustment may be necessary in reservoirs or reservoir areas that are sheltered from winds. The segment calibration factor for dispersion can be adjusted downward to reflect local restrictions caused by weirs, bridges, etc. Calibration of dispersion rates based upon tracer data is feasible only if significant tracer gradients are detected in the reservoir as a result of the tracer loading distributions.

Step 7 involves selecting, testing, and possibly calibrating nutrient sedimentation models using **List** and/or **Plot** procedures. Calibrating dispersion rates to match observed nutrient gradients is also feasible, provided that tracer data are not available in Step 6. As discussed above, differences between observed and predicted nutrient profiles may reflect random errors in the data, as well as true differences between the model predictions and reservoir responses. As discussed above, a conservative approach to calibration is recommended.

The **List/Compar** procedure provides statistical comparisons of observed and predicted concentrations. These are computed using three alternative measures of error: observed error only, T(1); error typical of model development data set, T(2); and observed and predicted error, T(3). Tests of model applicability are normally based upon T(2) and T(3). If their absolute values exceed 2 for the comparison of area-weighted mean concentrations, there is less than a 5-percent chance that nutrient sedimentation dynamics in the reservoir are typical of those in the model development data set, assuming that input conditions have been specified in an unbiased manner. The applicability of the models would be questionable in this case. If the discrepancy cannot be attributed to possible errors in the input data file (particularly, inflow concentrations), other options for modeling nutrient sedimentation should be investigated.

Lack of fit may also result from unsteady-state loading conditions, particularly if the nutrient turnover ratio is less than 2 based upon annual loadings. In such cases, averaging periods longer than a year may be required to establish a valid load/response relationship. This situation is more likely to occur for nitrogen than phosphorus because unit sedimentation rates tend to be lower for nitrogen.

Once an appropriate sedimentation model is selected, T(1) can be used as a basis for deciding whether calibration is appropriate. If the absolute value of T(1) exceeds 2, then there is less than a 5-percent chance that the observed and predicted means are equal, given the error in the observed mean. In this situation, it may be desirable to calibrate the model so that observed and predicted nutrient concentrations match.

As outlined in Table 4.2, two calibration methods are provided for phosphorus and nitrogen: Method 0 - calibrate decay rates and Method 1 - calibrate concentrations. In the first case, the segment-specific calibration factors are applied to estimated sedimentation rates in computing nutrient balances. In the second case, the factors are applied to estimated concentrations. In Method 0 (default), it is assumed that the error is attributed primarily to the sedimentation model. In Method 1, the error source is unspecified (some combination of input error, dispersion error, and sedimentation model error). The latter may be used when predicted nutrient profiles are insensitive to errors in predicted sedimentation rate because the mass balance is dominated by inflow and outflow terms (low hydraulic residence times, see Figures 1.3 and 1.4). Regardless of the selected calibration option, global calibration factors for phosphorus and nitrogen (specified on the **Case/Edit/Mcoef** screen) are always applied to the nutrient sedimentation rates.

Nutrient Sedimentation Models 1 and 2 have been empirically calibrated and tested for predicting reservoir-mean conditions. Error analysis calculations indicate that sedimentation rates predicted by these models are generally accurate to within a factor of 2 for phosphorus and a factor of 3 for nitrogen (Walker 1985). To account for this error, nutrient calibration factors (**Case/Edit/Mcoefs** screen) can be adjusted within the nominal ranges of 0.5 to 2.0 and 0.33 to 3 for phosphorus and nitrogen, respectively.

In some cases, nutrient retention coefficients for phosphorus or nitrogen may be negative. Even after setting the nutrient calibration coefficient to zero (essentially treating the nutrient as a conservative substance), the model will underpredict the observed nutrient concentration in the reservoir. This may reflect net nutrient releases from bottom sediments (phosphorus or nitrogen) or fixation of atmospheric nitrogen by bluegreen algae. These "internal sources" can be represented in the model using tributaries with TYPE CODE=5. Apparent negative retention coefficients may reflect use of an improper averaging period or underestimation of significant external loads. Independent evidence and estimates of sediment nutrient sources should be obtained before specifying internal sources in the model. As discussed in the Theory section of this chapter, reservoirs with negative nutrient retention coefficients were rarely encountered in the supporting research (Walker 1985). If internal sources are specified, estimates of model error derived from the supporting research are invalid. While it is usually possible to "tune" the model predictions using the internal source terms, this does not provide a way of predicting how the internal sources will change in response to changes in external loads or other management strategies evaluated in Step 11.

Once nutrient balances have been established, eutrophication responses (as measured by chlorophyll *a*, transparency, and hypolimnetic oxygen depletion rate) are developed in Step 8. This involves model selection, testing, and possible calibration. As outlined in Tables 4.2 and 4.3, several options are available for predicting chlorophyll *a* concentrations and Secchi depths as a function of nutrient levels and other controlling factors. If nitrogen balances are considered in addition to phosphorus, chlorophyll *a* Models 1 or 3 can be

used; otherwise, chlorophyll *a* Model 2 (default) is the most general for application to reservoirs. Secchi Model 1 (default) requires an estimate of nonalgal turbidity for each model segment (see Theory). The interpretation and use of t-statistics (**List/Compar** procedure) in testing and calibrating the chlorophyll *a* and Secchi submodels follow the above discussion for nutrients (Step 7).

With the completion of Step 8, the model has been set up and possibly calibrated using pool and tributary data from a particular year or growing season. Step 9 involves testing of the model based upon an independent data set derived from a different monitoring period. Model options and calibration factors are held constant, and performance is judged based upon a comparison of observed and predicted nutrient, chlorophyll *a*, and transparency profiles. This procedure is especially recommended in systems with significant year-to-year variations in hydrology, loading, and pool water quality conditions or in cases where extensive calibration is necessary. Generally, multiyear reservoir studies are necessary in order to obtain adequate perspectives on water quality variations driven by variations in climate or flow. A separate model input file can be created for each study year; each file uses the same segmentation scheme, model options, and calibration coefficients. Successful simulation of year-to-year variations is important evidence of model validity. Reiteration of previous modeling steps may be required to improve model performance over the range of monitored conditions.

Step 10 involves application of the model for diagnostic purposes using the **List/Diag** procedure. Observed and predicted variables are listed and ranked against the model development data set. Diagnostic variables (Table 4.5) reflect the relative importance of phosphorus, nitrogen, and light as factors controlling algal productivity. Results are reviewed to ensure that controlling factors are consistent with the chlorophyll *a* and transparency submodels employed.

The model is applied to predict the impacts of alternative loading scenarios or management strategies in Step 11. Typically, a separate input file is created for each management strategy and hydrologic condition (e.g., wet year, average year, dry year). Effects of management strategies under different hydrologic conditions can be evaluated by comparing model predictions. Model output from multiple runs can be routed to disk files and subsequently read into a spreadsheet for tabulation, comparison, and display. In simple cases, multiple loading scenarios can be specified within a single file (see Scheme 4 in Figure 4.3 or Instructional Cases at the end of this chapter).

Sensitivity to critical assumptions made in the modeling process can be evaluated by repeating Steps 1-11 using alternative assumptions and comparing results. If the application has involved substantial calibration in Steps 6-8, management scenarios should also be evaluated using model runs with the uncalibrated model (all calibration coefficients set to 1.0). In many cases, the relative impacts of alternative management strategies (expressed as percentage

differences in predicted mean chlorophyll *a*, for example) will be insensitive to whether they are based upon the calibrated or the uncalibrated model.

Error analyses can be run to quantify uncertainty in each predicted response variable for each scenario and hydrologic condition. Uncertainty is expressed in terms of the mean coefficient of variation (CV). The error analysis will overpredict this uncertainty in cases where the model has been calibrated and tested based upon site-specific conditions. In all cases, the uncertainty associated with relative predictions (e.g., expressed as percent change in chlorophyll *a* resulting from different management strategies) will be substantially lower than that associated with absolute predictions (expressed in ppb).

In applying the model to predict future conditions, diagnostic variables are checked to ensure that controlling factors are consistent with the chlorophyll *a* and transparency submodels. For example, if a phosphorus-limited chlorophyll *a* submodel (e.g., 4 or 5 in Table 4.2) is applied to existing conditions in Step 8, model predictions will be invalid for a future loading condition, which causes a switch from phosphorus- to nitrogen-limited conditions. Similarly, if the phosphorus sedimentation model does not account for inflow phosphorus availability, predictions of future conditions involving a significant change in the Ortho-P/Total P load ratio may be invalid.

Scenario B - Existing reservoir with pool water quality data only

BATHTUB can be used to summarize and rank water quality conditions and to evaluate controlling factors in segments representing different reservoirs or different areas within one reservoir. Comparisons are based upon observed water quality conditions and morphometric features specified for each segment. Various nutrient/chlorophyll *a* and other eutrophication response models can be tested. This type of analysis can be applied in the absence of nutrient loading and water balance information. It is essentially descriptive or diagnostic in nature and does not provide a predictive basis. Because water-balance and nutrient-balance calculations are not involved, Steps 4-7 and 11 are not performed.

Scenario C - Reservoir with loading data only

BATHTUB can be used to predict water quality conditions in a future reservoir or in an existing reservoir lacking observed water quality data. Lack of observed water quality data precludes calibration and testing of diffusive transport, nutrient sedimentation, and eutrophication-response models. If the application is to an existing reservoir, a monitoring program should be implemented to obtain data for calibration and testing before using the model to evaluate management strategies. If the application is to a proposed reservoir, the accuracy and credibility of model projections would be enhanced by first

applying it successfully to an existing reservoir in the same region and, if possible, with similar morphometry and watershed characteristics.

Model predictions for a future reservoir refer to steady-state conditions and do not apply to the initial "reservoir aging" period, during which significant "internal" loadings may occur as a result of nutrient releases from inundated soils and vegetation. The reservoir aging period is inherently dynamic and not suited for direct simulation via the steady-state algorithms used in BATHTUB. Approximate estimates of conditions during the reservoir aging period may be derived by specifying additional internal nutrient sources of appropriate magnitudes to reflect sediment releases during this period, based upon literature reviews and/or field data.

Procedure Outline

Following is a list of all BATHTUB procedures. Names are listed on the left. Indentation reflects Menu level (Lines 1-4). A brief description of each procedure is given on the right.

```
Case                Define Case - Read, Enter, Edit, or List Input Values

   Edit             Edit Case Data
      Dimensions    Edit Case Dimensions, File Name, Title, User Notes
      Globals       Edit Global Parameters, Precip., Evap., Atmospheric Loads...
      Segments      Edit Segments, Calib. Factors, Morphometry, Obs. Water Qual.
      Tribs         Edit Tributary & Watershed Data - Areas, Flows, Concs...
      Nonpoint      Edit Nonpoint Landuse Categories & Export Coefficients
         First      Edit Coefficients for Landuse Categories 1-4
         Second     Edit Coefficients for Landuse Categories 5-8
      MCoefs        Edit Default Model Coefficients & Error Terms
      Channels      Edit Transport Channels
      All           Edit All Input Data Groups

   Models           Set Model Options

   Read             Read Case Data File
      Data          Read Input File (Filename = *.BIN, BATHTUB Version >= 5.0)
      Translate     Read Old Input File Format (Filename = *.BTH, Version <= 4.4

   Save             Save Case Input Data File

   New              Reset Input Values & Start New Case


   Change           Delete, Insert, or Copy Segments or Tributaries
      Segments      Delete, Insert, or Copy Segments
         Delete     Delete a Segment from the Existing Network
         Insert     Insert a New Segment into the Network
         Copy       Copy Data from One Segment to Other Segment(s)
      Tribs         Delete, Insert, or Copy Tributaries/Watersheds
         Delete     Delete a Tributary from the Existing Network
         Insert     Insert a New Tributary into the Network
         Copy       Copy Data from One Tributary to Other Tributaries
   List             List Input Values for Current Case

   Morpho           List Segment Morphometry

Run                 Check Case Data & Run Model

   Model            Run Model
```

DATA-ENTRY SCREEN: Case/Edit/Globals

```
        GLOBAL VARIABLES & ATMOSPHERIC LOADS

                              MEAN      CV
AVERAGING PERIOD (YRS)  _______  ______
PRECIPITATION      (M)  _______  ______
EVAPORATION        (M)  _______  ______
STORAGE INCREASE   (M)  _______  ______

                     ATMOS. LOADS (KG/KM2-YR)
VARIABLE                  MEAN      CV      AVAILABILITY-FACTOR
TOTAL PHOSPHORUS        _______  ______        ______ [0.33]
ORTHO PHOSPHORUS        _______  ______        ______ [1.33]
TOTAL NITROGEN          _______  ______        ______ [0.59]
INORG. NITROGEN         _______  ______        ______ [0.79]
CONSERV. SUBST.         _______  ______
```

F1=HELP, F2=DONE/SAVE, F3=EDIT FIELD, F7=HELP/EDITOR, <ESC>=ABORT

HELP SCREEN:

```
Case Edit Globals

Values entered in this screen apply to all segments in network
during the period of mass-balance calculations.

Averaging Period = duration of mass-balance calculations
                 = period used in specifying tributary inflows
   (1 = annual, .5 = April-September, .42 = May-September)

Storage Increase = increase in pool elevation between start
    and end of Averaging Period.

Default values for Availability Factors are shown in [brackets].
```

DATA-ENTRY SCREEN: Case/Edit/Segments

```
SEGMENT: ___ NAME: _______________ OUTFLOW SEG:___ GROUP:___
AREA (KM2):_______ MEAN DEPTH (M):______ LENGTH (KM):______

 VARIABLE              UNITS      MEAN      CV      CALIBRATION
 MIXED LAYER DEPTH      (M)     _______  _______      FACTORS
 HYPOLIMNETIC DEPTH     (M)     _______  _______
 DISPERSION FACTOR       -                          _______ _____
 OBSERVED WATER QUALITY...
 NON-ALGAL TURBIDITY (1/M)      _______  _______
 TOTAL PHOSPHORUS      (PPB)    _______  _______   _______ _____
 TOTAL NITROGEN        (PPB)    _______  _______   _______ _____
 CHLOROPHYLL-A         (PPB)    _______  _______   _______ _____
 SECCHI DEPTH           (M)     _______  _______   _______ _____
 ORGANIC NITROGEN      (PPB)    _______  _______
 TOTAL P - ORTHO P     (PPB)    _______  _______
 HYPOL. O2 DEPL.     (PPB/DAY)  _______  _______   _______ _____
 METAL. O2 DEPL.     (PPB/DAY)  _______  _______
 CONSERVATIVE SUBST.     -      _______  _______
```

F1=HELP, F2=DONE/SAVE, F3=EDIT FIELD, F7=HELP/EDITOR, <ESC>=ABORT

Data-Entry Screens

Following is a listing of each data-entry screen in BATHTUB and its associated HELP file. These are accessed via the **Case/Edit** procedures. The **help** screens are accessed by hitting **<F1>**. Additional help screens containing more detailed information on specific fields may be obtained by moving the cursor to the field and hitting **<F8>**; this works only when the message '<F8> =HELP FIELD' appears in the lower right corner of the screen.

DATA-ENTRY SCREEN: Case/Edit/Dimensions

```
                CASE DIMENSIONS

CASE TITLE:      ____________________________
DATA FILE NAME:  ____________________________

NUMBER OF MODEL SEGMENTS ___ <=39

NUMBER OF TRIBUTARIES    ___ <=99
NOTES:
          ____________________________
          ____________________________
          ____________________________
          ____________________________
          ____________________________
          ____________________________
          ____________________________
          ____________________________
          ____________________________
          ____________________________
```

F1=HELP, F2=DONE/SAVE, F3=EDIT FIELD, F7=HELP/EDITOR, <ESC>=ABORT

HELP SCREEN:

```
Case Edit Dimensions

Define problem TITLE for labeling output

Define DATA FILE NAME for storing input values.  DOS PATH can also
be included. Examples:
      KEYSTONE.BIN       <---- places file in same directory as program
      C:\MYDIR\KEYSTONE.BIN
      D:\WORK\SUB\KEYSTONE.BIN

Extension '.BIN' should be used to indicate binary output format.

NUMBER OF SEGMENTS (Maximum = 39)

NUMBER OF TRIBUTARIES (Maximum = 99)
includes inflow streams, outflow streams, & non-point watersheds

NOTES are for user reference
```

NoError	Run Model Without Error Analysis
Inputs	Error Analysis - Case Input Variables Only
Model	Error Analysis - Model Error Terms & Segment Calib Factors
All	Error Analysis - All Input Variables and Model Parameters
Sensitivity	Run Sensitivity Analysis - Dispersion & Decay Factors
Conserv	Run Sensitivity Analysis for Conservative Substance Balance
Total P	Run Sensitivity Analysis for Total Phosphorus Balance
Total N	Run Sensitivity Analysis for Total Nitrogen Balance
List	List Model Output
Hydraul	List Morphometry / Hydraulics/ Dispersion Table
Balances	List Select Water and Mass Balances
Gross	Gross Water and Mass Balances - All Segments
By Segment	Water and Mass Balances by Segment - Detailed
Summary	Water and Mass Balances by Segment - Summary
Compar	Compare Observed & Predicted Values
All	All Segments + Area-Weighted Mean
Means	Area-Weighted Means Only
Diagnos	List Observed & Predicted Diagnostic Variables
All	All Segments + Area-Weighted Mean
Means	Area-Weighted Means Only
Profiles	List Summaries of Predicted & Observed Values
Predicted	List Predicted Values
Observed	List Observed Values
Ratios	List Observed / Predicted Ratios
Flownet	List Flow Network Summary
Table	List Table of Predicted Values for Selected Variables
Short	Short Table of Predicted Values by Segment
Plot	Plot Observed & Predicted Variables
Nutrients	Plot Total Phosphorus & Total Nitrogen Only
All	Plot All Variables
Some	Plot Selected Variable(s)
Define	Define Plot Scale Types (Default, Linear, or Logarithmic)
1Default	Use Default Scale Type for Each Variable
2Linear	Use Linear Scales for All Variables
3Log	Use Logarithmic Scales for All Variables
Utilities	Program Utilities
Output	Set Output Destination - Screen or File
Screen	Direct Output to Screen (Default)
File	Direct Output to Disk File
Restrict	Restrict Output & Plots to Specific Segment(s)
View	View any DOS Text File
Error	View Error Message File
Help	View Supplementary Help Screens
Quit	End Current Session

HELP SCREEN:

```
Case Edit Segments

Edit all input data & observed water quality for a specific segment.

Use cursor or space bar to select segment to be edited; press <return>
to select segment, <esc> to quit.

If mixed layer depth =0., it will be estimated from mean depth.

Calibration factors normally = 1.0.

Observed water quality data should reflect growing season.
They are optional.  '0' indicates missing.

Estimates of non-algal turbidity are required if Chlorophyll-a Model
1 or 2 is used.  If turbidity is set to 0.0, it is estimated from
observed Chl-a and Secchi if both are specified.
```

DATA-ENTRY SCREEN: Case/Edit/Tribs (TYPES 1-4, 6)

```
TRIBUTARY NUMBER:____   LABEL: ______________

SEGMENT NUMBER:  ____   TYPE CODE: _____

                                  MEAN       CV
 DRAINAGE AREA        (KM2)      ________
 FLOW                (HM3/YR)    ________   ________
 TOTAL PHOSPHORUS     (PPB)      ________   ________
 ORTHO PHOSPHORUS     (PPB)      ________   ________
 TOTAL NITROGEN       (PPB)      ________   ________
 INORGANIC NITROGEN   (PPB)      ________   ________
 CONSERVATIVE SUBST.   -         ________   ________

          NON-POINT-SOURCE WATERSHED AREAS
CATEGORY:  ________  ________  ________  ________
AREA (KM2) ________  ________  ________  ________
CATEGORY:  ________  ________  ________  ________
AREA (KM2) ________  ________  ________  ________
```

F1=HELP, F2=DONE/SAVE, F3=EDIT FIELD, F7=HELP/EDITOR, <ESC>=ABORT

HELP SCREEN:

```
Case Edit Tributary

Edit tributary names, types, flows, drainage areas, & concentrations.
Use cursor or space bar to select trib. to be edited;
press <return> to select tributary, <esc> to quit.

Tributary TYPE CODES:
  1 = Gauged Tributary (flow, concs input)
  2 = Ungauged Tributary (flows, concs estimated from land use)
  3 = Point Source Discharging Directly to Reservoir
  4 = Outflow or Withdrawal
  5 = Internal Source (input areal loads in mg/m2-day)
  6 = Diffusive Source

If TYPE=2, flow & concentrations will be estimated using the non-point
  source model, otherwise, values entered in this screen will be used.

Non-Point Source Watershed Areas:
-> only used in calculations if TYPE CODE=2
-> sum of subwatershed areas should equal total drainage area
-> landuse category definitions & export coefficients specified
      in separate screen ('Case Edit Nonpoint')
```

DATA-ENTRY SCREEN: Case/Edit/Tribs (TYPE = 5)

```
TRIBUTARY NUMBER:____   LABEL: ______________

SEGMENT NUMBER: ____    TYPE CODE: _____ =5

        INTERNAL LOADING RATES (MG/M2-DAY)

                          MEAN      CV
 TOTAL PHOSPHORUS         _______   _______

 ORTHO PHOSPHORUS         _______   _______

 TOTAL NITROGEN           _______   _______

 INORGANIC NITROGEN       _______   _______

 CONSERVATIVE SUBST.      _______   _______
```

F1=HELP, F2=DONE/SAVE, F3=EDIT FIELD, F7=HELP/EDITOR, <ESC>=ABORT

HELP SCREEN:

```
Internal Load Rates

Use tributary type code = 5 to specify internal loads for each
constituent to any segment in units of mg/m2-day.

This can be used to represent nutrient recycling from bottom
sediments, if independent estimates or measurements are
available.

To use this feature, change the tributary type code to 5 and
press <F2>.  The normal tributary input screen (used for
type codes 1-4) will switch to one with entry locations for
internal load rates and cvs for each constituent.
```

DATA-ENTRY SCREEN: Case/Edit/Nonpoint

NON-POINT-SOURCE EXPORT COEFFICIENTS

LANDUSE CAT: LABEL	1		2		3		4	
	MEAN	CV	MEAN	CV	MEAN	CV	MEAN	CV
RUNOFF M/YR	____	____	____	____	____	____	____	____
TOTAL P PPB	____	____	____	____	____	____	____	____
ORTHO P PPB	____	____	____	____	____	____	____	____
TOTAL N PPB	____	____	____	____	____	____	____	____
INORG N PPB	____	____	____	____	____	____	____	____
CONS S ---	____	____	____	____	____	____	____	____

F1=HELP, F2=DONE/SAVE, F3=EDIT FIELD, F7=HELP/EDITOR, <ESC>=ABORT

HELP SCREEN:

Case Edit Nonpoint

Edit Non-Point Source Export Coefficients

These values are used to estimate flow & concentration for TYPE=2 tributaries, according to the following model:

FLOW (hm3/yr) = SUM [AREA (km2) x RUNOFF (m/yr)]

LOAD (kg/yr) = SUM [AREA (km2) x RUNOFF (m/yr) x CONC (ppb)]

SUM = sum over land use categories

This screen is used to enter RUNOFF & CONC values for each landuse category.

This screen can be ignored if all inflows are measured directly.

DATA-ENTRY SCREEN: Case/Edit/Mcoefs

MODEL CALIBRATION FACTORS

	CURRENT-CASE MEAN	CURRENT-CASE CV	DEFAULT-VALUES MEAN	DEFAULT-VALUES CV
DISPERSION RATE	_____	_____	1.0	.70
P DECAY RATE	_____	_____	1.0	.45
N DECAY RATE	_____	_____	1.0	.55
CHL-A MODEL	_____	_____	1.0	.26
SECCHI MODEL	_____	_____	1.0	.10
ORGANIC N MODEL	_____	_____	1.0	.12
TP-OP MODEL	_____	_____	1.0	.15
HODV MODEL	_____	_____	1.0	.15
MODV MODEL	_____	_____	1.0	.22
SEC./CHLA SLOPE (M2/MG)	_____	_____	.025	.0
MINIMUM QS (M/YR)	_____	_____	4.0	.0
CHL-A FLUSHING TERM	_____	_____	1.0	.0
CHLOROPHYLL-A CV	_____		.62	

F1=HELP, F2=DONE/SAVE, F3=EDIT FIELD, F7=HELP/EDITOR, <ESC>=ABORT

HELP SCREEN:

```
Case Edit MCoefs

Edit Model Coefficients & Error Terms.

Calibration factors apply to all segments.

For example, changing the mean value for coefficient 1 (P DECAY RATE)
from 1.0 (default value) to 0.5 will reduce the phosphorus sedimentation
rate in all segments by 50%, regardless of which option is selected for
predicting phosphorus sedimentation.

Default values are listed on right.

MINIMUM QS = lowest overflow rate used in computing sedimentation coefs.

FLUSHING EFFECT = 1 include flushing term in Chl-a Models 1 & 2,
                = 0 exclude flushing term

CHL-A CV = Chl-a-a temporal coefficient of variation used in
        computing algal nuisance frequencies (typical value = .62)
```

DATA-ENTRY-SCREEN: Case/Edit/Channels

```
          DEFINE CHANNELS - TRANSPORT BETWEEN SEGMENTS

                 SEGMENTS   ADVECTIVE-FLOW   DIFFUSIVE-EXCHANGE
LABEL            FROM  TO     HM3/YR     CV     HM3/YR      CV
_______________  __  __  __________  ____  __________  ____
_______________  __  __  __________  ____  __________  ____
_______________  __  __  __________  ____  __________  ____
_______________  __  __  __________  ____  __________  ____
_______________  __  __  __________  ____  __________  ____
_______________  __  __  __________  ____  __________  ____
_______________  __  __  __________  ____  __________  ____
_______________  __  __  __________  ____  __________  ____
_______________  __  __  __________  ____  __________  ____
_______________  __  __  __________  ____  __________  ____

F1=HELP,  F2=DONE/SAVE,  F3=EDIT FIELD,  F7=HELP/EDITOR,  <ESC>=ABORT
```

HELP SCREEN:

```
Case Edit Channels

Defines Transport Channels (optional).

Specification of "Normal Outflow Segments" defines a typical application
consisting of a one-dimensional, branched network.

"Channels" can be used to specify additional advective flow and diffusiv
transport between any pair of segments.

Solutions of the water-balance and mass-balance equations are modified
to account for these additional transport terms.

Flow values must be estimated independently.

Up to 10 channels can be defined for any case.
```

Documented Session

This section describes examples of each output format using data from Keystone Reservoir (located on the Arkansas and Cimarron rivers in Oklahoma). Data from this reservoir are analyzed extensively in the supporting research document (Walker 1985). Model segmentation for Keystone is illustrated in Figure 4.9.

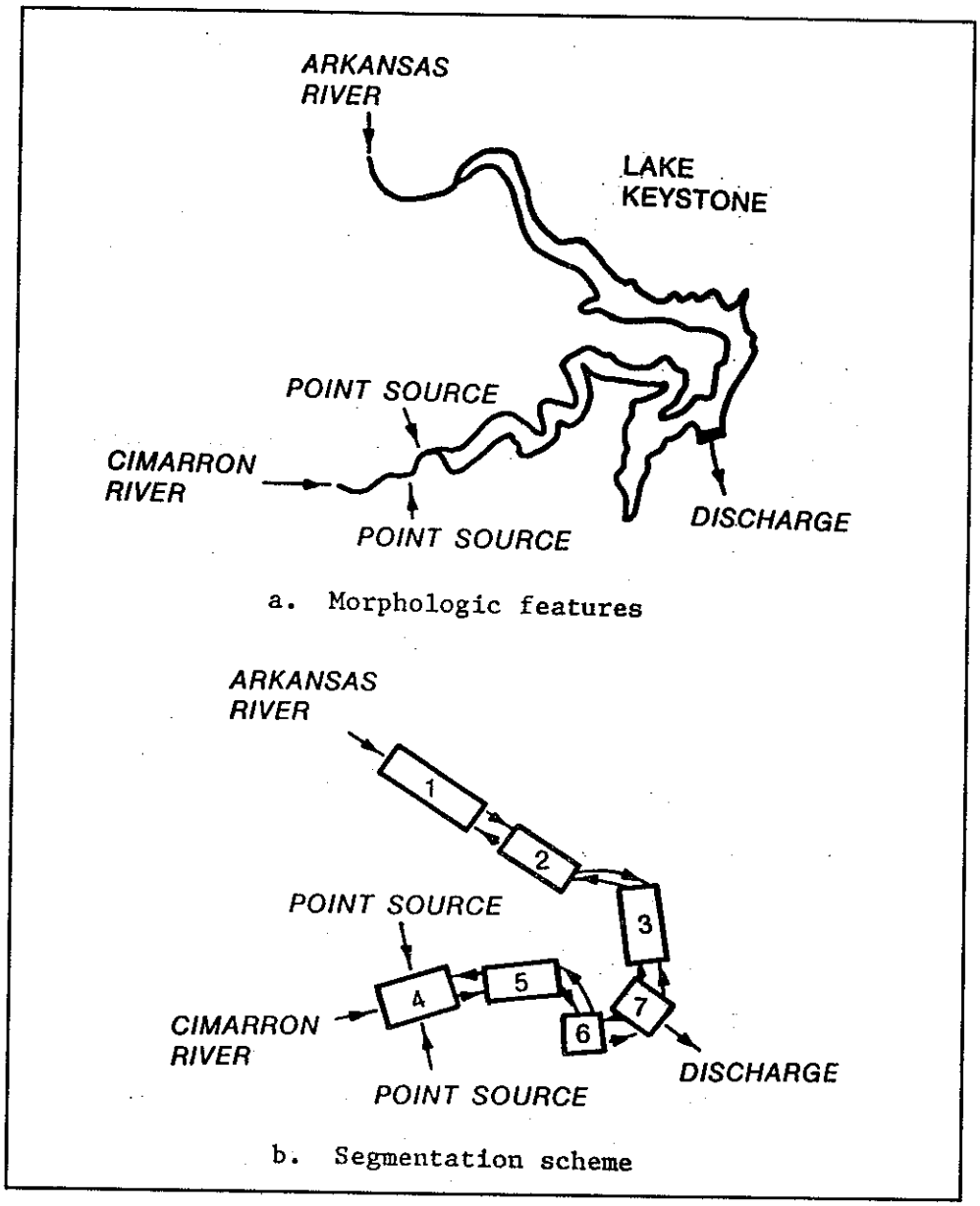


Figure 4.9. Model segmentation for Lake Keystone, Oklahoma, application

Pool and tributary water quality data were derived from measurements made in 1974 and 1975 by the EPA National Eutrophication Survey (NES) (U.S. Environmental Protection Agency) (USEPA 1975). The Keystone pool was sampled by the NES at nine stations four times between April and October 1975. The role of light limitation in Keystone has been previously discussed (Walker 1985). Because of the relatively low summer hydraulic residence time of the reservoir (0.08 year), seasonal nutrient turnover ratios are high, and water and mass balance calculations are based on May through September conditions during the pool monitoring year. Point sources include three sets of municipal sewage effluents which have been aggregated by reservoir segment. Since the NES estimated nutrient loadings but not flows for these effluents, a flow of 1 hm^3/year has been assumed for each source (insignificant in relation to reservoir water balance) and the nutrient concentrations have been adjusted to correspond with the reported loadings.

The input data file 'KEYSTONE.BIN' file (found on the distribution diskette and copied to the hard drive during installation) is used to generate the output listings. The following procedures are executed:

Case/Read/Data
Case/List
Case/Morpho
Run/Model/All
List/Hydraulics
List/Balances/Gross
List/Balances/By Segment
List/Balances/Summary
List/Compar/All
List/Diagnos/All
List/Profiles/Predicted
List/Table
List/Flownet
Run/Sensitivity/Total P
Plot/Some
Quit

Installing the program and running these procedures in sequence, while referring to comments and instructions below, will help users to become familiar with program operation and output formats.

Start the program from the DOS prompt by entering:

>BATHTUB

```
                    B A T H T U B

              EMPIRICAL MODELING OF
            RESERVOIR EUTROPHICATION

                  VERSION 5.3

            Environmental Laboratory
        USAE Waterways Experiment Station
             Vicksburg, Mississippi

                  March 1995

PRESS KEY TO CONTINUE, <ESC> RETURN TO MENU                100
```

A series of introductory screens appear. Pressing **<ESC>** *here bypasses the introductory screens and proceeds to the main program menu:*

```
                    B A T H T U B  -  VERSION 5.3
Case      Run      List      Plot      Utilities      Help      Quit
Edit    Models     Read      Save      New     Change    List    Morpho

     Define Case - Read, Enter, Edit, or List Input Values

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP

CASE = Default Input File        DATA FILE   =
SEGMENTS     =  1                TRIBUTARIES =  1

MODEL OPTION ----->                SELECTION ----->
CONSERVATIVE SUBSTANCE             0 NOT COMPUTED
PHOSPHORUS BALANCE                 1 2ND ORDER, AVAIL P
NITROGEN BALANCE                   0 2ND ORDER, AVAIL N
CHLOROPHYLL A                      1 P, N, LIGHT, T
SECCHI DEPTH                       1 VS. CHLA & TURBIDITY
DISPERSION                         1 FISCHER-NUMERIC
PHOSPHORUS CALIBRATION             1 DECAY RATES
NITROGEN CALIBRATION               1 DECAY RATES
```

Select ***Case/Read/Data*** *to read a BATHTUB data set (selected choices are underlined below but are highlighted on the screen). Choices are made in one of two ways: (a) by pressing the first letter of the desired command, or (b) by using the cursor keys. A one-line description of the selected procedure is highlighted at the bottom of the upper menu box.*

```
                    B A T H T U B  -  VERSION 5.3
Case      Run      List      Plot      Utilities      Help      Quit
Edit    Models     Read      Save      New     Change    List    Morpho
Data    Translat

     Read Input File (Filename = *.BIN, BATHTUB Versions >=5.0

 MOVE CURSOR & HIT <Enter> OR <First Letter> TO RUN ROUTINE, <F1,F7> HELP
```

The next screen asks the user to specify the DOS path to the directory where BATHTUB data sets are stored. If data sets are kept in the same directory as the BATHTUB program (as is recommended and assumed here), press **<Enter>**.

```
ENTER FILE PATH or PRESS <Esc> TO ENTER FILENAME DIRECTLY

ENTER FILE PATH: *.BIN
```

Press ***<Enter>***.

A listing of input files in the specified path is given. Files are identified by the .BIN extension.

```
POINT TO DESIRED FILE & PRESS <Enter>   PATH = *.BIN

  ----------SELECT FILE----------
  BEAVER.BIN
  CASE1.BIN
  CASE2.BIN
  CASE3.BIN
  CASE4.BIN
  CASE5.BIN
> KEYSTONE.BIN
```

Move the cursor to the desired input file and hit **<Enter>**.

```
CLEARING CURRENT CASE, OK ?
```

Respond with a **Y** *(yes) to clear the current data set and load the specified file.* ***Control*** *returns to the main menu.*

```
                    B A T H T U B  -  VERSION 5.3
Case     Run     List     Plot     Utilities     Help     Quit
Edit   Models    Read     Save     New    Change   List   Morpho

   Define Case - Read, Enter, Edit, or List Input Values

CASE = Keystone Reservoir, Oklahoma                DATA FILE  = KEYSTONE.BIN
SEGMENTS    =  7   TRIBUTARIES = 13      CHANNELS = 0

MODEL OPTION ----->                 SELECTION ----->
CONSERVATIVE SUBSTANCE              0 NOT COMPUTED
PHOSPHORUS BALANCE                  1 2ND ORDER, AVAIL P
NITROGEN BALANCE                    1 2ND ORDER, AVAIL N
CHLOROPHYLL-A                       1 P, N, LIGHT, T
SECCHI DEPTH                        1 VS. CHLA & TURBIDITY
DISPERSION                          1 FISCHER-NUMERIC
PHOSPHORUS CALIBRATION              1 DECAY RATES
NITROGEN CALIBRATION                1 DECAY RATES
AVAILABILITY FACTORS                1 USE FOR MODEL 1 ONLY
MASS-BALANCE TABLES                 1 USE ESTIMATED CONCENTRATIONS
```

The lower half of the screen summarizes the dimensions and selected model options for the current case. Input values can be listed by selecting ***Case/ List:***

```
B A T H T U B  -  VERSION 5.3
Case     Run     List     Plot     Utilities     Help     Quit
Edit     Models  Read     Save     New     Change     List     Morpho

   List Input Values for the Current Case
```

Keystone Reservoir, Oklahoma

MODEL OPTIONS:

1	CONSERVATIVE SUBSTANCE	0 NOT COMPUTED
2	PHOSPHORUS BALANCE	1 2ND ORDER, AVAIL P
3	NITROGEN BALANCE	1 2ND ORDER, AVAIL N
4	CHLOROPHYLL-A	1 P, N, LIGHT, T
5	SECCHI DEPTH	1 VS. CHLA & TURBIDITY
6	DISPERSION	1 FISCHER-NUMERIC
7	PHOSPHORUS CALIBRATION	1 DECAY RATES
8	NITROGEN CALIBRATION	1 DECAY RATES
9	ERROR ANALYSIS	1 MODEL & DATA
10	AVAILABILITY FACTORS	1 USE FOR MODEL 1 ONLY
11	MASS-BALANCE TABLES	1 USE ESTIMATED CONCS

ATMOSPHERIC LOADS & AVAILABILITY FACTORS:

VARIABLE	ATMOSPHERIC-LOADS KG/KM2-YR	CV	AVAILABILITY FACTOR
1 CONSERV	.00	.00	.00
2 TOTAL P	30.00	.50	.33
3 TOTAL N	1000.00	.50	.59
4 ORTHO P	15.00	.50	1.93
5 INORG N	500.00	.50	.79

GLOBAL INPUT VALUES:

PARAMETER	MEAN	CV
PERIOD LENGTH YRS	.420	.000
PRECIPITATION M	.530	.200
EVAPORATION M	.900	.300
INCREASE IN STORAGE M	.000	.000

TRIBUTARY DRAINAGE AREAS AND FLOWS:

ID	TYPE	SEG	NAME	DRAINAGE AREA KM2	MEAN FLOW HM3/YR	CV OF MEAN FLOW
1	4	7	ARKANSAS OUTFLOW	162804.000	10556.000	.100
2	1	1	ARKANSAS INFLOW	123625.000	6770.000	.100
3	1	1	HELLROARING	27.700	10.000	.100
4	1	4	CIMARRON	34929.000	2572.000	.100
5	1	4	LAGOON	123.000	37.000	.100
6	1	1	UNGAUGED-SEG 1	600.000	216.000	.200
7	1	2	UNGAUGED-SEG 2	400.000	143.000	.200
8	1	4	UNGAUGED-SEG 4	2440.000	736.000	.200
9	1	5	UNGAUGED-SEG 5	150.000	45.000	.200
10	1	6	UNGAUGED-SEG 6	400.000	120.000	.200
11	3	1	CLEVELAND STPS	.000	1.000	.200
12	3	4	CIMARRON STPS	.000	1.000	.200
13	3	6	MANNFORD STP	.000	1.000	.200

TRIBUTARY CONCENTRATIONS (PPB): MEAN/CV

ID	CONSERV	TOTAL P	TOTAL N	ORTHO P	INORG N
1	.0/ .00	109.0/ .04	1464.0/ .10	86.0/ .10	771.0/ .33
2	.0/ .00	570.0/ .20	2467.0/ .15	158.0/ .09	500.0/ .30
3	.0/ .00	72.0/ .22	1639.0/ .06	12.0/ .09	268.0/ .06
4	.0/ .00	364.0/ .11	1884.0/ .09	133.0/ .07	285.0/ .17
5	.0/ .00	150.0/ .19	1940.0/ .06	22.0/ .16	431.0/ .13
6	.0/ .00	72.0/ .30	1639.0/ .30	12.0/ .30	268.0/ .30
7	.0/ .00	72.0/ .30	1639.0/ .30	12.0/ .30	268.0/ .30
8	.0/ .00	150.0/ .30	1940.0/ .30	22.0/ .30	431.0/ .30
9	.0/ .00	150.0/ .30	1940.0/ .30	22.0/ .30	431.0/ .30

10	.0/	.00	150.0/	.30	1940.0/	.30	22.0/	.30	431.0/	.30
11	.0/	.00	4535.0/	.00	13605.0/	.00	4535.0/	.00	13605.0/	.00
12	.0/	.00	14261.0/	.00	38456.0/	.00	14261.0/	.00	38456.0/	.00
13	.0/	.00	1135.0/	.00	3400.0/	.00	1135.0/	.00	3400.0/	.00

MODEL SEGMENTS & CALIBRATION FACTORS:

SEG	OUTFLOW	GROUP	SEGMENT NAME		CALIBRATION FACTORS P SED	N SED	CHL-A	SECCHI	HOD	DISP
1	2	1	ARKANSAS UPPER		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
2	3	1	ARKANSAS MID		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
3	7	1	ARKANSAS LOWER		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
4	5	1	CIMARRON UPPER		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
5	6	1	CIMARRON MID		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
6	7	1	CIMARRON LOWER		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
7	0	1	DAM AREA		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000

SEGMENT MORPHOMETRY: MEAN/CV

ID	LABEL	LENGTH KM	AREA KM2	ZMEAN M	ZMIX M	ZHYP M
1	ARKANSAS UPPER	15.00	8.4000	1.20	1.20/ .12	.00/ .00
2	ARKANSAS MID	15.00	25.2000	7.17	5.75/ .12	.00/ .00
3	ARKANSAS LOWER	15.00	25.2000	8.77	6.37/ .12	.00/ .00
4	CIMARRON UPPER	15.00	8.4000	2.59	2.59/ .12	.00/ .00
5	CIMARRON MID	15.00	12.6000	7.17	5.75/ .12	.00/ .00
6	CIMARRON LOWER	15.00	21.0000	10.46	6.89/ .12	.00/ .00
7	DAM AREA	4.00	8.4000	13.05	7.45/ .12	.00/ .00

SEGMENT OBSERVED WATER QUALITY:

SEG		TURBID 1/M	CONSER ---	TOTALP MG/M3	TOTALN MG/M3	CHL-A MG/M3	SECCHI M	ORG-N MG/M3	TP-OP MG/M3	HODV MG/M3-D	MODV MG/M3-D
1	MN:	3.45	.0	367.0	1575.0	62.0	.2	856.0	250.0	.0	.0
	CV:	.39	.00	.09	.15	.62	.19	.14	.16	.00	.00
2	MN:	2.60	.0	.0	.0	.0	.0	.0	.0	.0	.0
	CV:	.40	.00	.00	.00	.00	.00	.00	.00	.00	.00
3	MN:	2.43	.0	149.0	1303.0	2.8	.4	523.0	48.0	.0	.0
	CV:	.31	.00	.14	.06	.48	.30	.09	.22	.00	.00
4	MN:	4.41	.0	234.0	1077.0	23.7	.2	700.0	148.0	.0	.0
	CV:	.66	.00	.11	.12	.53	.58	.06	.24	.00	.00
5	MN:	2.32	.0	130.0	1099.0	7.2	.4	573.0	51.0	.0	.0
	CV:	.25	.00	.15	.09	.61	.23	.05	.16	.00	.00
6	MN:	1.45	.0	99.0	1079.0	8.7	.6	508.0	37.0	.0	.0
	CV:	.30	.00	.13	.10	.44	.25	.07	.15	.00	.00
7	MN:	1.91	.0	145.0	1277.0	3.6	.5	453.0	34.0	.0	.0
	CV:	.30	.00	.18	.05	.57	.29	.02	.50	.00	.00

MODEL COEFFICIENTS:

COEFFICIENT	MEAN	CV
DISPERSION FACTOR	1.000	.70
P DECAY RATE	1.000	.45
N DECAY RATE	1.000	.55
CHL-A MODEL	1.000	.26
SECCHI MODEL	1.000	.10
ORGANIC N MODEL	1.000	.12
TP-OP MODEL	1.000	.15
HODV MODEL	1.000	.15
MODV MODEL	1.000	.22
BETA M2/MG	.025	.00
MINIMUM QS	4.000	.00
CHLA FLUSHING TE	1.000	.00
CHLOROPHYLL-A CV	.620	.00

CASE NOTES:
epa/nes data

The listing of input values can be used to check and/or document the input case file. The listing should be checked against original data sources to identify any data-entry errors.

The listing is copied to a temporary disk file and a file viewing utility is loaded. Function keys are identified at the bottom of the screen. The user can scroll forward or backward through the output listing by using the keypad arrows. The **<Home>** *key moves to the top of the file. The* **<End>** *key moves to the bottom of the file. A Help screen related to the current output listing can be viewed by pressing* **<F1>**. *The listing can be saved in a permanent disk file by pressing* **<F8>**. *Pressing* **<Esc>** *returns to the main menu. A short summary of segment morphometric features can be viewed by selecting* ***Case/Morpho:***

```
                    B A T H T U B  -  VERSION 5.3
Case      Run      List      Plot      Utilities      Help      Quit
Edit    Models     Read      Save      New     Change    List   Morpho

   List Segment Morphometry
```

```
CASE: Keystone Reservoir, Oklahoma
 Segment                  Area   Zmean  Length  Volume   Width     L/W
                           km2       m      km     hm3      km       -
  1 ARKANSAS UPPER        8.40    1.20   15.00    10.1     .56   26.79
  2 ARKANSAS MID         25.20    7.17   15.00   180.7    1.68    8.93
  3 ARKANSAS LOWER       25.20    8.77   15.00   221.0    1.68    8.93
  4 CIMARRON UPPER        8.40    2.59   15.00    21.8     .56   26.79
  5 CIMARRON MID         12.60    7.17   15.00    90.3     .84   17.86
  6 CIMARRON LOWER       21.00   10.46   15.00   219.7    1.40   10.71
  7 DAM AREA              8.40   13.05    4.00   109.6    2.10    1.90

 Total Area   =    109.20 km2
 Total Volume =    853.15 hm3
 Mean Depth   =      7.81 m
```

This procedure summarizes input morphometric data for each segment. Average segment width is calculated as the ratio of surface area to segment length. Total surface area, volume, and mean depth are also listed. The model can be executed with a full error analysis by selecting ***Run/Model/All:***

```
                    B A T H T U B  -  VERSION 5.3
Case      Run      List      Plot      Utilities      Help      Quit
Model   Sensitivity
NoError  Inputs   Model  All

   Error Analysis - All Input Variables and Model Parameters
```

The program first checks for invalid input values.

```
CHECKING INPUT VALUES...

INPUTS seem OK...
```

If input data errors are encountered or the mass-balance equations cannot be solved, error messages are listed here and control returns to the main menu. Otherwise, the error analysis proceeds:

```
                                                                    WAIT

ERROR ANALYSIS - SOLUTION AT ITERATION: 1696
 TESTING X  1644/ 1696 ITERATIONS =   1
```

After completing the error analysis, control returns to the main menu. A ***'Model Executed'*** *message appears in the lower right-hand corner of the screen. This indicates that the execution was successful and the* ***List*** *and* ***Plot*** *routines can be accessed to review results. Output screens and comments for* ***List*** *procedures are given below. Menu screens are not repeated.*

```
B A T H T U B  -  VERSION 5.3
Case      Run       List      Plot      Utilities    Help      Quit
Hydraul   Balances  Compar    Diagnos   Profiles     Flownet   Table  Short

   List Model Output
```

Procedure: List / Hydraul

CASE: Keystone Reservoir, Oklahoma

HYDRAULIC AND DISPERSION PARAMETERS:

SEG	OUT	NET INFLOW HM3/YR	RESIDENCE TIME YRS	OVERFLOW RATE M/YR	MEAN VELOCITY KM/YR	----DISPERSION----- ESTIMATED KM2/YR	NUMERIC KM2/YR	EXCHANGE RATE HM3/YR
1	2	6989.60	.00144	832.1	10401.2	279864.	78009.	9043.
2	3	7110.40	.02541	282.2	590.3	31846.	4427.	22018.
3	7	7088.20	.03118	281.3	481.1	21914.	3608.	17981.
4	5	3338.60	.00652	397.5	2301.8	32455.	17264.	1469.
5	6	3372.50	.02679	267.7	560.0	7552.	4200.	1346.
6	7	3475.00	.06321	165.5	237.3	6474.	1780.	4582.
7	0	10555.80	.01038	1256.6	385.2	19633.	770.	0.

This output format summarizes segment linkages and flows between model segments. The net inflow represents sum of inflows (external + outflow from upstream segments + precipitation) minus evaporation. Dispersion and exchange rates are calculated according to the specified dispersion model (see Table 4.2). Numeric dispersion rates are subtracted from estimated dispersion rates before calculating exchange flows. Model segmentation should be designed so that estimated dispersion exceeds numeric dispersion in each segment. Numeric dispersion rates can be reduced by decreasing segment lengths. The exchange rate represents the diffusive exchange between each segment (SEG) and its downstream segment (OUT).

Procedure: List / Balances / Gross

CASE: Keystone Reservoir, Oklahoma
GROSS WATER BALANCE:

ID	T	LOCATION	DRAINAGE AREA KM2	---- FLOW (HM3/YR) ---- MEAN	VARIANCE	CV	RUNOFF M/YR
1	4	ARKANSAS OUTFLOW	162804.000	10556.000	.111E+07	.100	.065
2	1	ARKANSAS INFLOW	123625.000	6770.000	.458E+06	.100	.055
3	1	HELLROARING	27.700	10.000	.100E+01	.100	.361

4	1 CIMARRON	34929.000	2572.000	.662E+05	.100	.074
5	1 LAGOON	123.000	37.000	.137E+02	.100	.301
6	1 UNGAUGED-SEG 1	600.000	216.000	.187E+04	.200	.360
7	1 UNGAUGED-SEG 2	400.000	143.000	.818E+03	.200	.357
8	1 UNGAUGED-SEG 4	2440.000	736.000	.217E+05	.200	.302
9	1 UNGAUGED-SEG 5	150.000	45.000	.810E+02	.200	.300
10	1 UNGAUGED-SEG 6	400.000	120.000	.576E+03	.200	.300
11	3 CLEVELAND STPS	.000	1.000	.400E-01	.200	.000
12	3 CIMARRON STPS	.000	1.000	.400E-01	.200	.000
13	3 MANNFORD STP	.000	1.000	.400E-01	.200	.000
PRECIPITATION		109.200	137.800	.760E+03	.200	1.262
TRIBUTARY INFLOW		325389.400	10649.000	.550E+06	.070	.033
POINT-SOURCE INFLOW		.000	3.000	.120E+00	.115	.000
***TOTAL INFLOW		325498.600	10789.800	.550E+06	.069	.033
GAUGED OUTFLOW		162804.000	10556.000	.111E+07	.100	.065
ADVECTIVE OUTFLOW		162694.600	-.201	.167E+07	9.990	.000
***TOTAL OUTFLOW		325498.600	10555.800	.555E+06	.071	.032
***EVAPORATION		.000	234.000	.493E+04	.300	.000

GROSS MASS BALANCE BASED UPON ESTIMATED CONCENTRATIONS
COMPONENT: TOTAL P

			----- LOADING ----		--- VARIANCE ---			CONC	EXPORT
ID	T	LOCATION	KG/YR	%(I)	KG/YR**2	%(I)	CV	MG/M3	KG/KM2
1	4	ARKANSAS OUTFLOW	1400865.0	31.4	.132E+12	40.9	.259	132.7	8.6
2	1	ARKANSAS INFLOW	3337881.0	74.8	.305E+12	94.9	.166	493.0	27.0
3	1	HELLROARING	469.2	.0	.755E+04	.0	.185	46.9	16.9
4	1	CIMARRON	969155.3	21.7	.158E+11	4.9	.130	376.8	27.7
5	1	LAGOON	3402.5	.1	.475E+06	.0	.203	92.0	27.7
6	1	UNGAUGED-SEG 1	10134.7	.2	.134E+08	.0	.361	46.9	16.9
7	1	UNGAUGED-SEG 2	6709.6	.2	.585E+07	.0	.361	46.9	16.8
8	1	UNGAUGED-SEG 4	67682.6	1.5	.596E+09	.2	.361	92.0	27.7
9	1	UNGAUGED-SEG 5	4138.2	.1	.223E+07	.0	.361	92.0	27.6
10	1	UNGAUGED-SEG 6	11035.2	.2	.158E+08	.0	.361	92.0	27.6
11	3	CLEVELAND STPS	10249.1	.2	.420E+07	.0	.200	10249.1	.0
12	3	CIMARRON STPS	32229.9	.7	.416E+08	.0	.200	32229.9	.0
13	3	MANNFORD STP	2565.1	.1	.263E+06	.0	.200	2565.1	.0
PRECIPITATION			4242.4	.1	.450E+07	.0	.500	30.8	38.8
TRIBUTARY INFLOW			4410608.0	98.9	.322E+12	100.0	.129	414.2	13.6
POINT-SOURCE INFLOW			45044.1	1.0	.460E+08	.0	.151	15014.7	.0
***TOTAL INFLOW			4459894.0	100.0	.322E+12	100.0	.127	413.3	13.7
GAUGED OUTFLOW			1400865.0	31.4	.132E+12	40.9	.259	132.7	8.6
ADVECTIVE OUTFLOW			-26.6	.0	.296E+11	9.2	9.999	132.7	.0
***TOTAL OUTFLOW			1400839.0	31.4	.133E+12	41.2	.260	132.7	4.3
***RETENTION			3059056.0	68.6	.275E+12	85.6	.172	.0	.0

	HYDRAULIC	---------- TOTAL P ----------			
OVERFLOW RATE	RESIDENCE TIME	POOL RESIDENCE CONC	TIME	TURNOVER RATIO	RETENTION COEF
M/YR	YRS	MG/M3	YRS	-	-
96.66	.0808	163.6	.0313	13.4246	.6859

The output format summarizes the water and mass balance calculations over the entire reservoir. Results for the Total N balance are not shown. Results are reviewed to ensure that an accurate water balance has been established and that all drainage areas have been accounted for before proceeding to subsequent modeling steps. The output includes a mean, variance, and CV for each water and mass balance term. In the case of the mass balance, loading means and variances are also expressed as percentages of the total inflow mean and variance, respectively. These provide perspectives on predominant loading and error sources. The variance distribution can be used to prioritize

future data collection efforts by keying on the major sources of error (e.g., by increasing sampling frequencies).

The tables also include hydrologic summary statistics (surface overflow rate and hydraulic residence time) and mass balance statistics (mass residence time, turnover ratio, and retention coefficient). As discussed above, the mass residence time and turnover ratio are used in selecting an appropriate averaging period for water and mass balance calculations.

In the case of the Keystone phosphorus balance, the turnover ratio is 13.4, which means that phosphorus stored in the water column was displaced approximately 13.4 times during the 5-month balance period based upon observed pool phosphorus concentrations. This is a relatively favorable ratio for mass balance modeling because it indicates that pool nutrient levels are not likely to reflect loading conditions experienced prior to the mass balance period. As discussed above, a turnover ratio of 2 or more is desirable for modeling purposes.

Procedure: List / Balances / Detailed

```
SEGMENT BALANCE BASED UPON ESTIMATED CONCENTRATIONS
COMPONENT: TOTAL P                          SEGMENT:  3 ARKANSAS LOWER
                          --- FLOW ---        --- LOAD ---          CONC
ID  T LOCATION            HM3/YR      %        KG/YR      %        MG/M3
-----------------------------------------------------------------------
-----------------------------------------------------------------------
PRECIPITATION               31.80    .4        979.0     .1         30.8
ADVECTIVE INFLOW          7110.40   99.6    1366361.0   73.5        192.2
NET DIFFUSIVE INFLOW          .00     .0     492427.5   26.5           .0
***TOTAL INFLOW           7142.20  100.0    1859768.0  100.0        260.4
ADVECTIVE OUTFLOW         7088.20   99.2    1085383.0   58.4        153.1
***TOTAL OUTFLOW          7088.20   99.2    1085383.0   58.4        153.1
***EVAPORATION              54.00     .8          .0     .0           .0
***RETENTION                  .00     .0     774385.1   41.6           .0
-----------------------------------------------------------------------
RESID. TIME =    .031 YRS, OVERFLOW RATE =   281.3 M/YR, DEPTH =   8.8 M

SEGMENT BALANCE BASED UPON ESTIMATED CONCENTRATIONS
COMPONENT: TOTAL N                          SEGMENT:  3 ARKANSAS LOWER
                          --- FLOW ---        --- LOAD ---          CONC
ID  T LOCATION            HM3/YR      %        KG/YR      %        MG/M3
-----------------------------------------------------------------------
-----------------------------------------------------------------------
PRECIPITATION               31.80    .4      24822.0     .2        780.6
ADVECTIVE INFLOW          7110.40   99.6    9592980.0   92.2       1349.1
NET DIFFUSIVE INFLOW          .00     .0     791456.0    7.6           .0
***TOTAL INFLOW           7142.20  100.0   10409260.0  100.0       1457.4
ADVECTIVE OUTFLOW         7088.20   99.2    8937663.0   85.9       1260.9
***TOTAL OUTFLOW          7088.20   99.2    8937663.0   85.9       1260.9
***EVAPORATION              54.00     .8          .0     .0           .0
***RETENTION                  .00     .0    1471595.0   14.1           .0
-----------------------------------------------------------------------
RESID. TIME =    .031 YRS, OVERFLOW RATE =   281.3 M/YR, DEPTH =   8.8 M
```

This output format presents detailed water and mass balances by segment. Results are shown only for Segment 3. The summary includes flow, load, and mean concentration for each external source, discharge, and computed summary term. The summary terms include internal transfers (attributed to advection and exchange with neighboring segments) as well as external inputs,

outflows, and retention. The advective outflow term for each segment is derived from the flow balance.

Procedure: List / Balances / Summary

CASE: Keystone Reservoir, Oklahoma

WATER BALANCE TERMS (HM3/YR):

SEG	INFLOWS EXTERNAL	INFLOWS PRECIP	INFLOWS ADVECT	STORAGE INCREASE	OUTFLOWS ADVECT	OUTFLOWS DISCH	DOWNSTR EXCHANGE	EVAP
1	.700E+04	.106E+02	.000E+00	.000E+00	.699E+04	.000E+00	.904E+04	.180E+02
2	.143E+03	.318E+02	.699E+04	.000E+00	.711E+04	.000E+00	.220E+05	.540E+02
3	.000E+00	.318E+02	.711E+04	.000E+00	.709E+04	.000E+00	.180E+05	.540E+02
4	.335E+04	.106E+02	.000E+00	.000E+00	.334E+04	.000E+00	.147E+04	.180E+02
5	.450E+02	.159E+02	.334E+04	.000E+00	.337E+04	.000E+00	.135E+04	.270E+02
6	.121E+03	.265E+02	.337E+04	.000E+00	.348E+04	.000E+00	.458E+04	.450E+02
7	.000E+00	.106E+02	.106E+05	.000E+00	-.201E+00	.106E+05	.000E+00	.180E+02
NET	.107E+05	.138E+03	.000E+00	.000E+00	-.201E+00	.106E+05	.000E+00	.234E+03

MASS BALANCE TERMS (KG/YR) FOR: TOTAL P BASED UPON ESTIMATED CONCS:

SEG	INFLOWS EXTERNAL	INFLOWS ATMOSP	INFLOWS ADVECT	STORAGE INCREASE	OUTFLOWS ADVECT	OUTFLOWS DISCH	NET EXCHANGE	NET RETENT
1	.336E+07	.326E+03	.000E+00	.000E+00	.216E+07	.000E+00	-.106E+07	.144E+06
2	.671E+04	.979E+03	.216E+07	.000E+00	.137E+07	.000E+00	.196E+06	.997E+06
3	.000E+00	.979E+03	.137E+07	.000E+00	.109E+07	.000E+00	.492E+06	.774E+06
4	.107E+07	.326E+03	.000E+00	.000E+00	.779E+06	.000E+00	-.117E+06	.177E+06
5	.414E+04	.490E+03	.779E+06	.000E+00	.517E+06	.000E+00	.518E+05	.318E+06
6	.136E+05	.816E+03	.517E+06	.000E+00	.364E+06	.000E+00	.193E+06	.361E+06
7	.000E+00	.326E+03	.145E+07	.000E+00	-.266E+02	.115E+07	.239E+06	.539E+06
NET	.446E+07	.424E+04	.000E+00	.000E+00	-.266E+02	.115E+07	.000E+00	.331E+07

MASS BALANCE TERMS (KG/YR) FOR: TOTAL N BASED UPON ESTIMATED CONCS:

SEG	INFLOWS EXTERNAL	INFLOWS ATMOSP	INFLOWS ADVECT	STORAGE INCREASE	OUTFLOWS ADVECT	OUTFLOWS DISCH	NET EXCHANGE	NET RETENT
1	.128E+08	.827E+04	.000E+00	.000E+00	.109E+08	.000E+00	-.186E+07	.102E+06
2	.169E+06	.248E+05	.109E+08	.000E+00	.959E+07	.000E+00	-.871E+05	.138E+07
3	.000E+00	.248E+05	.959E+07	.000E+00	.894E+07	.000E+00	.791E+06	.147E+07
4	.464E+07	.827E+04	.000E+00	.000E+00	.431E+07	.000E+00	-.183E+06	.152E+06
5	.668E+05	.124E+05	.431E+07	.000E+00	.394E+07	.000E+00	.611E+05	.516E+06
6	.183E+06	.207E+05	.394E+07	.000E+00	.374E+07	.000E+00	.670E+06	.107E+07
7	.000E+00	.827E+04	.127E+08	.000E+00	-.240E+03	.155E+08	.603E+06	-.216E+07
NET	.179E+08	.108E+06	.000E+00	.000E+00	-.240E+03	.155E+08	.000E+00	.252E+07

This is a condensed version of the water and mass balances by segment. Summary terms are presented in tables that depict the routing of water and nutrient mass through the reservoir segments. Inflow terms include external watershed loadings, atmospheric loadings, and advection from upstream segments. Outflow terms include advection to downstream segments and specified withdrawals or discharges. The water balance also includes storage, evaporation, and gross diffusive exchange with downstream segments, although the latter is not a factor in the water balance calculation because it occurs in both directions. The mass balance tables also include storage, retention, and net

exchange with adjacent (upstream and downstream) segments. In the mass balances, the net exchange term is formulated as an input (i.e., it will be positive or negative), depending upon whether dispersion causes net transport of mass into or out of the segment, respectively.

Note that the advective outflow from each segment is calculated from the water balance. If the computed advective outflow from any segment (except those segments that discharge out of the system) is less than zero, the water and balances are satisfied by backflow from downstream segments (i.e., the direction of the advective flow at the corresponding segment interface is reversed). This might occur, for example, for a segment in which the evaporation rate exceeds the sum of external inflow and precipitation. The program handles this condition by reversing the flow direction. Solutions to water-balance and mass-balance equations cannot be obtained if the net water inflow for the entire reservoir (sum of inflows + precipitation - evaporation) is negative.

In the last (near-dam) segment, the advective outflow term of the water balance table represents the cumulative water balance error if the reservoir discharge rate is specified. In the Keystone example, a residual water balance error of -0.2 hm^3/year is indicated. Since this is small relative to the gauged outflow (10,556 hm^3/ year), the impact on the water and nutrient balance calculations is negligible. This water balance has been achieved by adjusting flow rates specified for ungauged drainage areas.

Procedure: List / Compar

```
CASE: Keystone Reservoir, Oklahoma

T STATISTICS COMPARE OBSERVED AND PREDICTED MEANS
USING THE FOLLOWING ERROR TERMS:
 1 = OBSERVED WATER QUALITY ERROR ONLY
 2 = ERROR TYPICAL OF MODEL DEVELOPMENT DATA SET
 3 = OBSERVED AND PREDICTED ERROR
```

SEGMENT: 1 ARKANSAS UPPER

VARIABLE		OBSERVED MEAN	OBSERVED CV	ESTIMATED MEAN	ESTIMATED CV	RATIO	T STATISTICS 1	T STATISTICS 2	T STATISTICS 3
TOTAL P	MG/M3	367.0	.09	308.9	.25	1.19	1.91	.64	.64
TOTAL N	MG/M3	1575.0	.15	1554.3	.19	1.01	.09	.06	.05
C.NUTRIENT	MG/M3	113.0	.14	109.4	.20	1.03	.24	.16	.13
CHL-A	MG/M3	62.0	.62	40.1	.36	1.55	.70	1.26	.61
SECCHI	M	.2	.19	.2	.29	.89	-.61	-.41	-.34
ORGANIC N	MG/M3	856.0	.14	1331.3	.25	.64	-3.15	-1.77	-1.53
TP-ORTHO-P	MG/M3	250.0	.16	149.1	.25	1.68	3.23	1.41	1.73

etc.. for segments 2-6

SEGMENT: 7 DAM AREA

VARIABLE		OBSERVED MEAN	OBSERVED CV	ESTIMATED MEAN	ESTIMATED CV	RATIO	T STATISTICS 1	T STATISTICS 2	T STATISTICS 3
TOTAL P	MG/M3	145.0	.18	132.7	.24	1.09	.49	.33	.30
TOTAL N	MG/M3	1277.0	.05	1196.9	.17	1.07	1.30	.29	.37
C.NUTRIENT	MG/M3	78.8	.10	72.9	.16	1.08	.77	.39	.42
CHL-A	MG/M3	3.6	.57	5.5	.38	.65	-.74	-1.23	-.62
SECCHI	M	.5	.29	.5	.28	1.02	.08	.08	.06
ORGANIC N	MG/M3	453.0	.02	426.2	.16	1.06	3.04	.24	.39
TP-ORTHO-P	MG/M3	34.0	.50	51.0	.28	.67	-.81	-1.11	-.71

SEGMENT: 8 AREA-WTD MEAN

VARIABLE		OBSERVED MEAN	OBSERVED CV	ESTIMATED MEAN	ESTIMATED CV	RATIO	T STATISTICS 1	T STATISTICS 2	T STATISTICS 3
TOTAL P	MG/M3	163.6	.13	169.5	.17	.97	-.28	-.13	-.16
TOTAL N	MG/M3	1218.4	.09	1255.2	.14	.97	-.33	-.14	-.18
C.NUTRIENT	MG/M3	76.1	.11	80.1	.13	.95	-.47	-.25	-.30
CHL-A	MG/M3	13.0	.56	9.6	.29	1.35	.53	.87	.47
SECCHI	M	.4	.28	.4	.16	1.03	.10	.10	.09
ORGANIC N	MG/M3	570.8	.08	562.1	.16	1.02	.20	.06	.08
TP-ORTHO-P	MG/M3	74.5	.20	71.3	.20	1.04	.21	.12	.15

This format compares observed and predicted water quality conditions in each model segment. It can be used to test model applicability to reservoirs with adequate water quality monitoring data. Area-weighted means across all reservoir segments are also calculated and compared. T-statistics compare observed and predicted means on logarithmic scales using three alternative measures of error:

a. *The first test considers error in the observed value only, as specified in Input Group 10. If the absolute value of the T(1) is less than 2.0, the observed mean is not significantly different from the predicted mean at the 95-percent confidence level, given the precision in the observed mean value, which reflects variability in the monitoring data and sampling program design.*

b. *The second test (supplementary to the third) compares the error with the standard error estimated from the model development data set and is independent of the observed and estimated CVs.*

c. *The third test considers observed and predicted CVs for each case, variable, and segment. If the absolute value of T(3) exceeds 2, the difference between the observed and predicted means is greater than expected (at the 95-percent confidence level), given potential errors in the observed water quality data, model input data, and inherent model errors.*

Since deviations would be expected to occur by chance in 5 percent of the tests applied to reservoirs conforming to the models, results of the T-tests should be interpreted cautiously. Error terms used in calculating T(2) and T(3) have been calibrated for predicting area-weighted mean conditions; observed versus predicted deviations may be greater for station-mean or segment-mean values.

In calculating the CVs for area-weighted mean observed conditions, the program attributes the major source of error to temporal variance and assumes that the errors are correlated across stations. Note that comparisons of area-weighted mean conditions are to be accurate only if sampling stations are distributed throughout the reservoir. If data sets do not provide adequate spatial coverage, the observed/predicted comparisons must be based upon data from individual segments with sufficient data.

Procedure: List / Diagnos

CASE: Keystone Reservoir, Oklahoma

OBSERVED AND PREDICTED DIAGNOSTIC VARIABLES
RANKED AGAINST CE MODEL DEVELOPMENT DATA SET

SEGMENT: 7 DAM AREA

VARIABLE		----- VALUES ----- OBSERVED	ESTIMATED	--- RANKS (%) --- OBSERVED	ESTIMATED
TOTAL P	MG/M3	145.00	132.71	89.1	87.1
TOTAL N	MG/M3	1277.00	1196.90	64.8	60.9
C.NUTRIENT	MG/M3	78.83	72.90	83.9	81.4
CHL-A	MG/M3	3.60	5.50	10.7	24.4
SECCHI	M	.50	.49	15.5	14.8
ORGANIC N	MG/M3	453.00	426.24	46.5	41.7
TP-ORTHO-P	MG/M3	34.00	50.96	55.2	71.2
ANTILOG PC-1		323.73	387.01	58.4	63.6
ANTILOG PC-2		1.66	2.21	.5	2.1
(N - 150) / P		7.77	7.89	12.5	13.0
INORGANIC N / P		7.42	9.43	8.2	12.4
TURBIDITY	1/M	1.91	1.91	90.3	90.3
ZMIX * TURBIDITY		14.23	14.23	97.4	97.4
ZMIX / SECCHI		14.90	15.25	97.5	97.7
CHL-A * SECCHI		1.80	2.69	.7	3.0
CHL-A / TOTAL P		.02	.04	.1	.7
FREQ(CHL-a>10)	%	2.51	10.13	.0	.0
FREQ(CHL-a>20)	%	.11	.84	.0	.0
FREQ(CHL-a>30)	%	.01	.12	.0	.0
FREQ(CHL-a>40)	%	.00	.02	.0	.0
FREQ(CHL-a>50)	%	.00	.01	.0	.0
FREQ(CHL-a>60)	%	.00	.00	.0	.0
CARLSON TSI-P		75.91	74.64	.0	.0
CARLSON TSI-CHLA		43.17	47.32	.0	.0
CARLSON TSI-SEC		69.99	70.33	.0	.0

This format lists observed values, estimated values, and error ratios and ranks them against the model development data set. Approximate rankings are computed from the geometric mean and geometric standard deviation of area-weighted mean observed values in the model development data set assuming a log-normal distribution. The variable list includes the basic network variables plus nine composite variables that are useful for diagnostic purposes. Diagnostic variables are used to assess the relative importance of phosphorus, nitrogen, and light as controlling factors, as outlined in Table 4.6.

Procedure: List / Profiles

CASE: Keystone Reservoir, Oklahoma

PREDICTED CONCENTRATIONS:

VARIABLE	SEGMENT-->	1	2	3	4	5	6
		7	8				
TOTAL P	MG/M3	308.93	192.16	153.13	233.24	153.42	104.83
		132.71	169.46				
TOTAL N	MG/M3	1554.32	1349.15	1260.92	1291.77	1167.48	1077.22
		1196.90	1255.19				
C.NUTRIENT	MG/M3	109.44	88.66	79.22	88.10	74.21	62.20
		72.90	80.07				
CHL-A	MG/M3	40.11	6.88	5.96	13.60	6.93	6.92
		5.50	9.65				
SECCHI	M	.22	.36	.39	.21	.40	.62
		.49	.41				
ORGANIC N	MG/M3	1331.32	509.55	475.98	798.97	489.75	423.97
		426.24	562.13				
TP-ORTHO-P	MG/M3	149.06	69.76	64.11	124.57	63.22	42.57
		50.96	71.34				

This is a short summary of predicted concentrations in each model segment.

Procedure: List / Flownet

SEGMENT NETWORK: FLOWS IN HM3/YR

		INFLOW	OUTFLOW	EXCHANGE
********** SEGMENT:	1 ARKANSAS UPPER	INFLOW	OUTFLOW	EXCHANGE
PRECIP AND EVAPORATION:		10.60	18.00	
EXTERNAL INFLOW:	2 ARKANSAS INFLOW	6770.00		
EXTERNAL INFLOW:	3 HELLROARING	10.00		
EXTERNAL INFLOW:	6 UNGAUGED-SEG 1	216.00		
EXTERNAL INFLOW:	11 CLEVELAND STPS	1.00		
DISCHARGE TO SEGMENT:	2 ARKANSAS MID		6989.60	9043.10
********** SEGMENT:	2 ARKANSAS MID	INFLOW	OUTFLOW	EXCHANGE
PRECIP AND EVAPORATION:		31.80	54.00	
INFLOW FROM SEGMENT:	1 ARKANSAS UPPER	6989.60		9043.10
EXTERNAL INFLOW:	7 UNGAUGED-SEG 2	143.00		
DISCHARGE TO SEGMENT:	3 ARKANSAS LOWER		7110.40	22018.01
********** SEGMENT:	3 ARKANSAS LOWER	INFLOW	OUTFLOW	EXCHANGE
PRECIP AND EVAPORATION:		31.80	54.00	
INFLOW FROM SEGMENT:	2 ARKANSAS MID	7110.40		22018.01
DISCHARGE TO SEGMENT:	7 DAM AREA		7088.20	17980.92
********** SEGMENT:	4 CIMARRON UPPER	INFLOW	OUTFLOW	EXCHANGE
PRECIP AND EVAPORATION:		10.60	18.00	
EXTERNAL INFLOW:	4 CIMARRON	2572.00		
EXTERNAL INFLOW:	5 LAGOON	37.00		
EXTERNAL INFLOW:	8 UNGAUGED-SEG 4	736.00		
EXTERNAL INFLOW:	12 CIMARRON STPS	1.00		
DISCHARGE TO SEGMENT:	5 CIMARRON MID		3338.60	1468.88
********** SEGMENT:	5 CIMARRON MID	INFLOW	OUTFLOW	EXCHANGE
PRECIP AND EVAPORATION:		15.90	27.00	
INFLOW FROM SEGMENT:	4 CIMARRON UPPER	3338.60		1468.88
EXTERNAL INFLOW:	9 UNGAUGED-SEG 5	45.00		
DISCHARGE TO SEGMENT:	6 CIMARRON LOWER		3372.50	1346.13
********** SEGMENT:	6 CIMARRON LOWER	INFLOW	OUTFLOW	EXCHANGE
PRECIP AND EVAPORATION:		26.50	45.00	
INFLOW FROM SEGMENT:	5 CIMARRON MID	3372.50		1346.13
EXTERNAL INFLOW:	10 UNGAUGED-SEG 6	120.00		
EXTERNAL INFLOW:	13 MANNFORD STP	1.00		

```
   DISCHARGE TO SEGMENT:  7 DAM AREA                          3475.00    4582.44

*************** SEGMENT:  7 DAM AREA              INFLOW    OUTFLOW   EXCHANGE
 PRECIP AND EVAPORATION:                            10.60      18.00
    INFLOW FROM SEGMENT:  3 ARKANSAS LOWER        7088.20               17980.92
    INFLOW FROM SEGMENT:  6 CIMARRON LOWER        3475.00                4582.44
   OUTFLOW / WITHDRAWAL:  1 ARKANSAS OUTFLOW               10556.00
DISCHARGE OUT OF SYSTEM:                                      -.20
```

This format summarizes the water balance for each segment. Inflow, outflow, and exchange terms are listed. This is helpful for checking segment/tributary linkage against schematic diagrams such as Figure 4.9.

Procedure: List / Table

```
CASE: Keystone Reservoir, Oklahoma

TOTAL P    MG/M3
TOTAL N    MG/M3
CHL-A      MG/M3
SECCHI         M

Segment              TOTAL P  TOTAL N  CHL-A    SECCHI
 1 ARKANSAS UPPER      308.93  1554.32   40.11      .22
 2 ARKANSAS MID        192.16  1349.15    6.88      .36
 3 ARKANSAS LOWER      153.13  1260.92    5.96      .39
 4 CIMARRON UPPER      233.24  1291.77   13.60      .21
 5 CIMARRON MID        153.42  1167.48    6.93      .40
 6 CIMARRON LOWER      104.83  1077.22    6.92      .62
 7 DAM AREA            132.71  1196.90    5.50      .49
 8 AREA-WTD MEAN       169.46  1255.19    9.65      .41
```

User selects variables to be included from a list of all predicted variables. Values for Total P, Total N, Chl a, and Secchi are selected in this example.

Procedure: List / Short

```
Keystone Reservoir, Oklahoma

SEGMENT = 1 ARKANSAS UPPER
CONSERVATIVE SUB=      .0  TOTAL P    MG/M3=   308.9  TOTAL N    MG/M3=  1554.3
CHL-A      MG/M3=    40.1  SECCHI         M=      .2  ORGANIC N  MG/M3=  1331.3
TP-ORTHO-P MG/M3=   149.1  HOD-V  MG/M3-DAY=      .0  MOD-V  MG/M3-DAY=      .0
C.NUTRIENT MG/M3=   109.4  ANTILOG PC-1    =  3207.1  ANTILOG PC-2    =     5.7
(N - 150) / P   =     4.5  ZMIX * TURBIDITY=     4.1  ZMIX / SECCHI   =     5.3
CHL-A * SECCHI  =     9.0  CHL-A / TOTAL P =      .1  TURBIDITY    1/M=     3.4
INORGANIC N / P =     1.4  FREQ(CHL-a>10) %=    97.3  FREQ(CHL-a>20) %=    79.2
FREQ(CHL-a>30) %=    56.3  FREQ(CHL-a>40) %=    38.0  FREQ(CHL-a>50) %=    25.3
FREQ(CHL-a>60) %=    16.9  CARLSON TSI-P   =    86.8  CARLSON TSI-CHLA=    66.8
CARLSON TSI-SEC =    81.5

SEGMENT = 4 CIMARRON UPPER
CONSERVATIVE SUB=      .0  TOTAL P    MG/M3=   233.2  TOTAL N    MG/M3=  1291.8
CHL-A      MG/M3=    13.6  SECCHI         M=      .2  ORGANIC N  MG/M3=   799.0
TP-ORTHO-P MG/M3=   124.6  HOD-V  MG/M3-DAY=      .0  MOD-V  MG/M3-DAY=      .0
C.NUTRIENT MG/M3=    88.1  ANTILOG PC-1    =  1332.2  ANTILOG PC-2    =     2.5
(N - 150) / P   =     4.9  ZMIX * TURBIDITY=    11.4  ZMIX / SECCHI   =    12.3
CHL-A * SECCHI  =     2.9  CHL-A / TOTAL P =      .1  TURBIDITY    1/M=     4.4
INORGANIC N / P =     4.5  FREQ(CHL-a>10) %=    57.4  FREQ(CHL-a>20) %=    17.6
FREQ(CHL-a>30) %=     5.6  FREQ(CHL-a>40) %=     2.0  FREQ(CHL-a>50) %=      .8
FREQ(CHL-a>60) %=      .3  CARLSON TSI-P   =    82.8  CARLSON TSI-CHLA=    56.2
CARLSON TSI-SEC =    82.4
```

```
SEGMENT = 7 DAM AREA
CONSERVATIVE SUB=      .0  TOTAL P     MG/M3=   132.7  TOTAL N     MG/M3=  1196.9
CHL-A       MG/M3=    5.5  SECCHI          M=      .5  ORGANIC N  MG/M3=   426.2
TP-ORTHO-P MG/M3=    51.0  HOD-V  MG/M3-DAY=      .0  MOD-V  MG/M3-DAY=      .0
C.NUTRIENT MG/M3=    72.9  ANTILOG PC-1     =  387.0  ANTILOG PC-2     =     2.2
(N - 150) / P   =     7.9  ZMIX * TURBIDITY=    14.2  ZMIX / SECCHI    =    15.3
CHL-A * SECCHI  =     2.7  CHL-A / TOTAL P =      .0  TURBIDITY     1/M=     1.9
INORGANIC N / P =     9.4  FREQ(CHL-a>10) %=    10.1  FREQ(CHL-a>20) %=      .8
FREQ(CHL-a>30) %=      .1  FREQ(CHL-a>40) %=      .0  FREQ(CHL-a>50) %=      .0
FREQ(CHL-a>60) %=      .0  CARLSON TSI-P    =    74.6  CARLSON TSI-CHLA=    47.3
CARLSON TSI-SEC =    70.3
```

Procedure: Run / Sensitivity / Total P

```
PROFILE SENSITIVITY ANALYSIS FOR: TOTAL P
DECAY DISPERSION     SEGMENT
FACTOR FACTOR      1      2      3      4      5      6      7      8

   .50    .25  458.0  276.5  202.0  282.5  200.5  125.0  163.0  227.1
   .50   1.00  339.2  239.6  203.2  259.6  193.8  148.8  181.8  213.2
   .50   4.00  245.9  211.7  199.5  214.6  188.8  176.8  191.6  200.8

  1.00    .25  439.0  219.6  144.6  257.0  157.1   86.3  111.8  180.9
  1.00   1.00  308.9  192.2  153.1  233.2  153.4  104.8  132.7  169.5
  1.00   4.00  207.1  167.5  153.8  181.3  148.2  131.4  145.7  157.6

  2.00    .25  408.6  166.1   98.0  223.8  115.7   56.4   72.5  139.4
  2.00   1.00  279.3  149.7  110.7  202.8  115.4   70.1   92.4  131.1
  2.00   4.00  173.8  129.8  115.2  151.5  113.2   94.0  107.1  121.0

OBSERVED:       367.0     .0  149.0  234.0  130.0   99.0  145.0  163.6
```

This procedure tests the sensitivity analysis of predicted concentrations to longitudinal dispersion and decay (sedimentation) rates. These are two major factors controlling the prediction of spatial gradients in reservoirs. Dispersion rates are varied by a factor of 4, and decay rates, by a factor of 2, in rough proportion to expected error magnitudes for nutrient sedimentation options 1 or 2 and dispersion option 1 (Walker 1985). Generally, concentrations tend to be more sensitive to dispersion in upper-pool segments, where dispersion accounts for dilution of major inflows. Sensitivity to decay rate is usually greater in near-dam segments, as compared with upper-pool segments.

***Plot** procedures compare observed and predicted concentrations in each model segment. The **Plot/Some** procedure is demonstrated below:*

```
B A T H T U B  -  VERSION 5.3
Case      Run      List     Plot     Utilities     Help     Quit
Nutrients  All     Some     Define

  Plot Selected Variable(s)
```

```
SELECT VARIABLES TO BE PLOTTED
```

```
VARIABLE
CONSERVATIVE SUB
TOTAL P     MG/M3
TOTAL N     MG/M3
CHL A       MG/M3
SECCHI          M
ORGANIC N   MG/M3
TP-ORTHO-P MG/M3
HOD-V  MG/M3-DAY
MOD-V  MG/M3-DAY
C.NUTRIENT MG/M3
ANTILOG PC-1
ANTILOG PC-2
(N - 150) / P
ZMIX * TURBIDITY
ZMIX / SECCHI
CHL A * SECCHI
CHL A / TOTAL P
TURBIDITY     1/M
```

PRESS <SPACE> TO SELECT(*) OR NO( ), <ENTER>=DONE, <a>= ALL, <n>=NONE

These variables are identified in Table 4.6. The list extends below those listed in the window; to see the remainder of the list, press **<PgDn>**. *For demonstration purposes,* ***Total P, Total N, Chl a,*** *and* ***Secchi*** *are selected by moving the cursor to each field and pressing the* **<Space>** *bar:*

SELECT VARIABLES TO BE PLOTTED

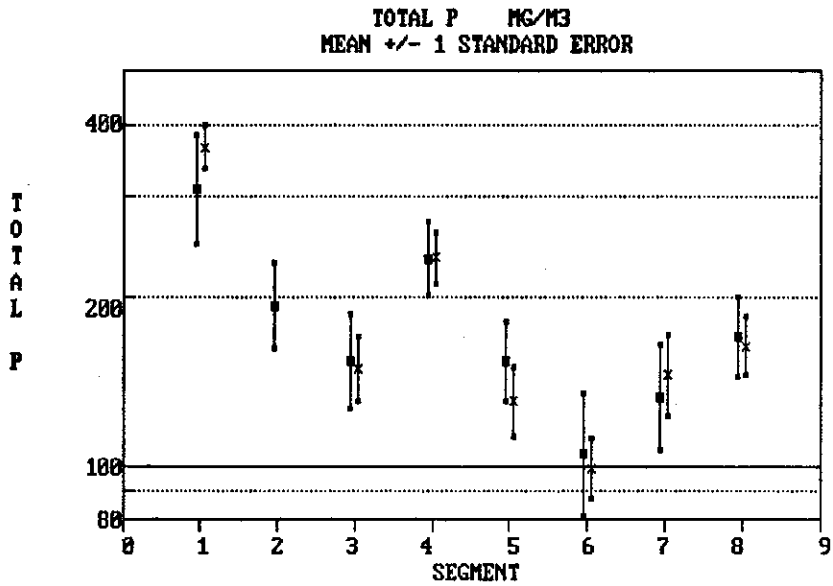
```
  VARIABLE
  CONSERVATIVE SUB
* TOTAL P     MG/M3
* TOTAL N     MG/M3
* CHL A       MG/M3
* SECCHI          M
  ORGANIC N   MG/M3
  TP-ORTHO-P MG/M3
  HOD-V  MG/M3-DAY
  MOD-V  MG/M3-DAY
  C.NUTRIENT MG/M3
  ANTILOG PC-1
  ANTILOG PC-2
  (N - 150) / P
  ZMIX * TURBIDITY
  ZMIX / SECCHI
  CHL A * SECCHI
  CHL A / TOTAL P
  TURBIDITY     1/M
```

PRESS <SPACE> TO SELECT(*) OR NO( ), <ENTER>=DONE, <a>= ALL, <n>=NONE

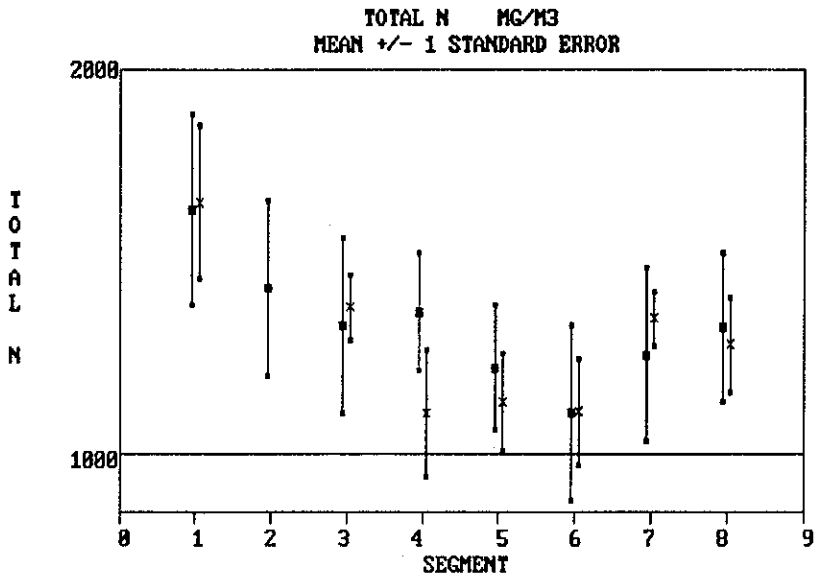
Plot format is selected from the following choices:

```
  SELECT PLOT FORMAT
> OBS, EST vs. SEGMENT
  OBSERVED VS. PREDICTED
  OBS/PREDICTED RATIOS
  ALL
```

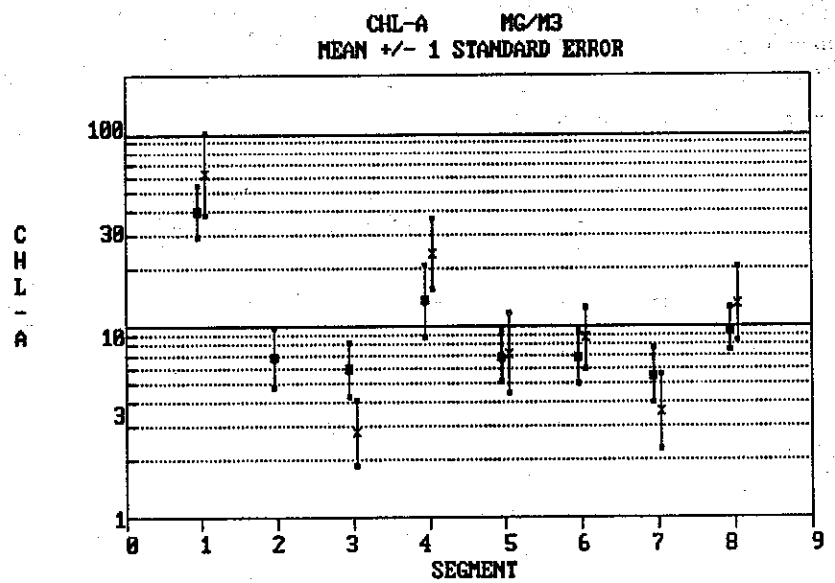
The first format is selected for demonstration. This compares observed and predicted concentrations by model segment. Solid symbols are mean values. Vertical lines are mean ± 1 standard error. Plots that follow are in the same order as the selected variable list.



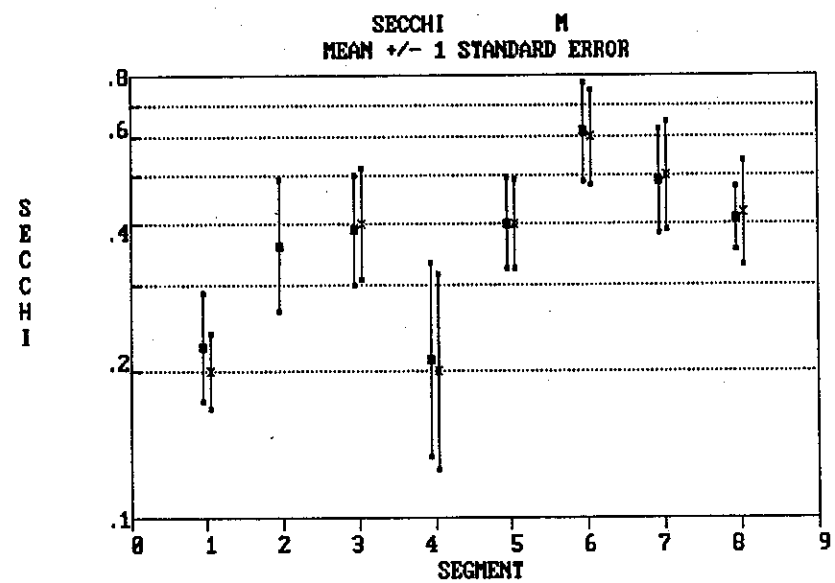
■ ESTIMATE × OBSERVED



■ ESTIMATE × OBSERVED



■ ESTIMATE × OBSERVED



■ ESTIMATE × OBSERVED

*Select **Quit** to end the session.*

```
B A T H T U B  -  VERSION 5.3
Case    Run    List    Plot    Utilities    Help    Quit

Quit ?
```

Input files should be saved before quitting. Type 'Y' or 'y' to end session. Type any other key to return to menu.

Instructional Cases

The following hypothetical cases illustrate BATHTUB applications to predict among-reservoir or within-reservoir (spatial or temporal) variations in trophic-state indicators. Each case is described by (a) a basic data sheet showing the segmentation scheme and essential input data and (b) a listing of BATHTUB input file (default option and model settings excluded). The following examples are presented:

Case	Segmentation Scheme
1	Single reservoir, spatially averaged
2	Single reservoir, spatially segmented
3	Reservoir embayment, spatially segmented
4	Single reservoir, spatially averaged, multiple scenario
5	Collection of reservoirs, spatially averaged

These simple cases can be used for training purposes or as templates for creating real applications. An input file for each case is supplied with the program. The following procedure is suggested:

a. Select application of interest from listings below.

b. Review basic data sheet.

c. Review listing of BATHTUB input values.

d. Start program, read case data file, and execute model.

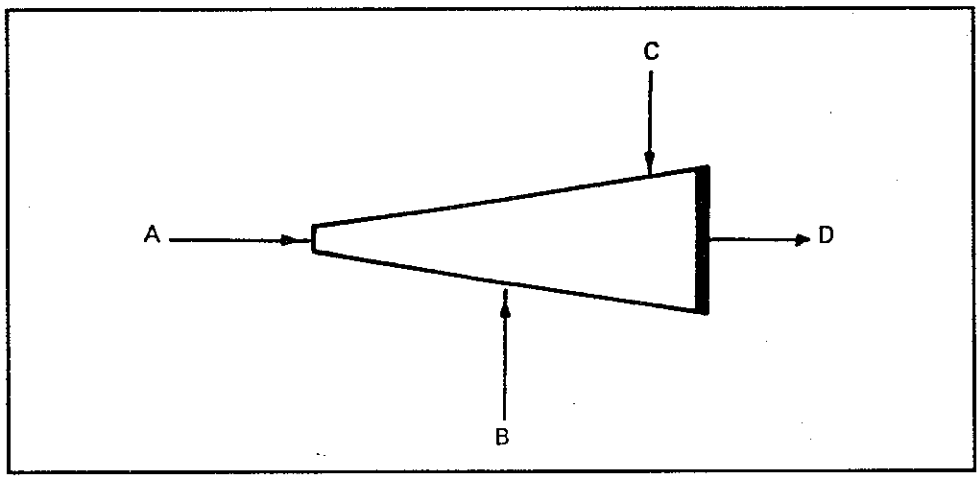
e. List and review model output.

f. Plot observed and predicted variables.

g. Edit case data and rerun the model to evaluate sensitivity to loadings or other input parameters of interest.

Basic data sheet for Case 1

Single reservoir, spatially averaged



Mass Balance Period: 1 October 1979 - 1 October 1980

Stream Monitoring Data:

Stream	Drainage Area km^2	Mean Flow hm^3/yr	Flow-Weighted Total P Concentration ppb
A	380	1,014	60
B	100	300	167
C	50	150	167
D	570	1,430	(Not Measured)

Atmospheric total P load = 30 kg/km^2-yr
Precipitation rate = 0.7 m/yr
Evaporation rate = 1.0 m/yr
Reservoir total volume = 704 hm^3
Reservoir total surface area = 40 km^2
Reservoir total length = 30 km
Reservoir surface elevation 1 Oct 1979 = 180.0 m
Reservoir surface elevation 1 Oct 1980 = 179.5 m
Observed pool water quality data: None

Listing of input values for Case 1

Single Reservoir, 1 Segment

ATMOSPHERIC LOADS & AVAILABILITY FACTORS:

VARIABLE	ATMOSPHERIC-LOADS KG/KM2-YR	CV	AVAILABILITY FACTOR
1 CONSERV	.00	.00	.00
2 TOTAL P	30.00	.50	1.00
3 TOTAL N	1000.00	.50	.59
4 ORTHO P	15.00	.50	.00
5 INORG N	500.00	.50	.79

GLOBAL INPUT VALUES:

PARAMETER		MEAN	CV
PERIOD LENGTH	YRS	1.000	.000
PRECIPITATION	M	.000	.200
EVAPORATION	M	.000	.300
INCREASE IN STORAGE	M	.000	.000

```
TRIBUTARY DRAINAGE AREAS AND FLOWS:
ID TYPE SEG NAME              DRAINAGE AREA    MEAN FLOW  CV OF MEAN FLOW
                                        KM2       HM3/YR
 1   1    1 stream a              380.000      1014.000        .000
 2   1    1 stream b              100.000       300.000        .000
 3   1    1 stream c               50.000       150.000        .000
 4   4    1 outflow d             570.000      1430.000        .000

TRIBUTARY CONCENTRATIONS (PPB): MEAN/CV
ID        CONSERV       TOTAL P       TOTAL N       ORTHO P       INORG N
 1       .0/ .00     60.0/ .00       .0/ .00       .0/ .00       .0/ .00
 2       .0/ .00    167.0/ .00       .0/ .00       .0/ .00       .0/ .00
 3       .0/ .00    167.0/ .00       .0/ .00       .0/ .00       .0/ .00
 4       .0/ .00       .0/ .00       .0/ .00       .0/ .00       .0/ .00

MODEL SEGMENTS & CALIBRATION FACTORS:
                                      ----------- CALIBRATION FACTORS -----------
SEG OUTFLOW GROUP SEGMENT NAME      P SED  N SED  CHL-A SECCHI    HOD      DISP
 1       0     1  single            1.00   1.00   1.00   1.00   1.00     1.000
                                CV:  .000   .000   .000   .000   .000      .000

SEGMENT MORPHOMETRY: MEAN/CV
                          LENGTH      AREA  ZMEAN      ZMIX       ZHYP
ID LABEL                     KM       KM2      M         M          M
 1 single                  30.00   40.0000  17.60   8.03/ .12    .00/ .00

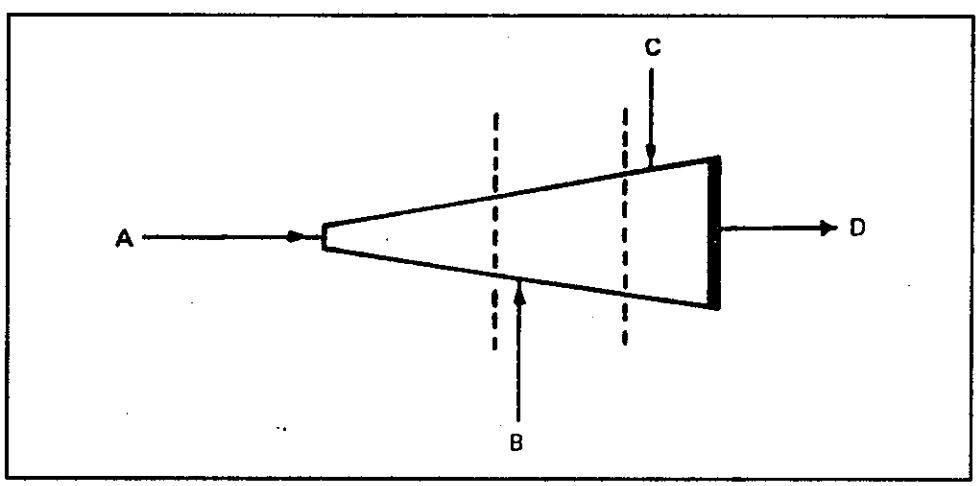
SEGMENT OBSERVED WATER QUALITY:
SEG     TURBID CONSER TOTALP TOTALN  CHL-A SECCHI  ORG-N  TP-OP   HODV   MODV
          1/M   ---   MG/M3  MG/M3  MG/M3      M  MG/M3  MG/M3 MG/M3-D MG/M3-D
 1 MN:    .10     .0     .0     .0     .0     .0     .0     .0     .0     .0
   CV:    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00

CASE NOTES:
single reservoir

spatially averaged
```

Basic data sheet for Case 2

Single Reservoir, Spatially Segmented



Mass Balance Period: 1 October 1979 - 1 October 1980

Stream Monitoring Data: Same as CASE 1

Segment Morphometry:

Segment	Surface Area km^2	Volume hm^3	Length km
Upper	8	64	10
Middle	16	256	10
Lower	16	384	10

Atmospheric total P load = 30 kg/km^2-yr
Precipitation rate = 0.7 m/yr
Evaporation rate = 1.0 m/yr
Reservoir surface elevation 1 Oct 1979 = 180.0 m
Reservoir surface elevation 1 Oct 1980 = 179.5 m
Observed pool water quality data: None

Listing of input values for Case 2

1 Reservoir, 3 Segments

ATMOSPHERIC LOADS & AVAILABILITY FACTORS:

VARIABLE	ATMOSPHERIC-LOADS KG/KM2-YR	CV	AVAILABILITY FACTOR
1 CONSERV	.00	.00	.00
2 TOTAL P	30.00	.00	1.00
3 TOTAL N	.00	.00	.00
4 ORTHO P	.00	.00	.00
5 INORG N	.00	.00	.00

GLOBAL INPUT VALUES:

PARAMETER		MEAN	CV
PERIOD LENGTH	YRS	1.000	.000
PRECIPITATION M		.700	.000
EVAPORATION M		1.000	.000
INCREASE IN STORAGE M		-.500	.000

TRIBUTARY DRAINAGE AREAS AND FLOWS:

ID	TYPE	SEG	NAME	DRAINAGE AREA KM2	MEAN FLOW HM3/YR	CV OF MEAN FLOW
1	1	1	Stream A	380.000	1014.000	.000
2	1	2	Stream B	100.000	300.000	.000
3	1	3	Stream C	50.000	150.000	.000
4	4	3	Stream D	570.000	1430.000	.000

TRIBUTARY CONCENTRATIONS (PPB): MEAN/CV

ID	CONSERV	TOTAL P	TOTAL N	ORTHO P	INORG N
1	.0/ .00	60.0/ .00	.0/ .00	.0/ .00	.0/ .00
2	.0/ .00	167.0/ .00	.0/ .00	.0/ .00	.0/ .00
3	.0/ .00	167.0/ .00	.0/ .00	.0/ .00	.0/ .00
4	.0/ .00	.0/ .00	.0/ .00	.0/ .00	.0/ .00

MODEL SEGMENTS & CALIBRATION FACTORS:

SEG	OUTFLOW	GROUP	SEGMENT NAME		P SED	N SED	CHL-A	SECCHI	HOD	DISP
					---------- CALIBRATION FACTORS ----------					
1	2	1	Upper Pool		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
2	3	1	Mid Pool		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
3	0	1	Near Dam		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000

SEGMENT MORPHOMETRY: MEAN/CV

ID	LABEL	LENGTH KM	AREA KM2	ZMEAN M	ZMIX M	ZHYP M
1	Upper Pool	10.00	8.0000	8.00	6.09/ .12	.00/ .00
2	Mid Pool	10.00	16.0000	16.00	7.87/ .12	.00/ .00
3	Near Dam	10.00	16.0000	24.00	8.35/ .12	.00/ .00

SEGMENT OBSERVED WATER QUALITY:

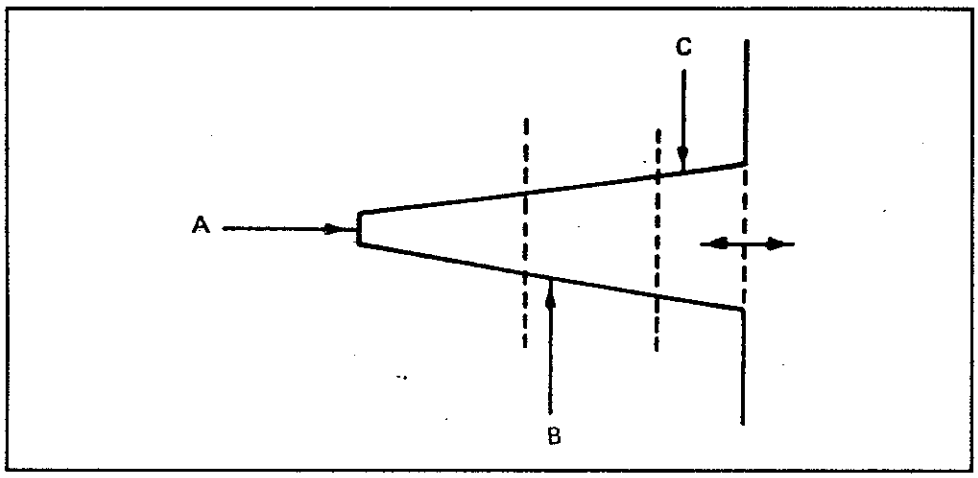
SEG	TURBID 1/M	CONSER ---	TOTALP MG/M3	TOTALN MG/M3	CHL-A MG/M3	SECCHI M	ORG-N MG/M3	TP-OP MG/M3	HODV MG/M3-D	MODV MG/M3-D
1 MN:	.00	.0	.0	.0	.0	.0	.0	.0	.0	.0
CV:	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
2 MN:	.00	.0	.0	.0	.0	.0	.0	.0	.0	.0
CV:	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
3 MN:	.00	.0	.0	.0	.0	.0	.0	.0	.0	.0
CV:	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

CASE NOTES:
single reservoir

3 segments

Basic data sheet for Case 3

Reservoir Embayment, Spatially Segmented



Mass Balance Period: 1 October 1979 - 1 October 1980

Stream Monitoring Data: Same as CASE 1

Segment Morphometry: Same as CASE 2

Estimated diffusive exchange with main reservoir = 2,000 hm^3/yr
Total P concentration in main reservoir = 15 mg/m^3

Atmospheric total p load = 30 kg/km^2-yr
Precipitation rate = 0.7 m/yr
Evaporation rate = 1.0 m/yr
Reservoir surface elevation 1 Oct 1979 = 180.0 m
Reservoir surface elevation 1 Oct 1980 = 179.5 m
Observed pool water quality data: None

Listing of input values for Case 3

Segmented Res. Embayment

ATMOSPHERIC LOADS & AVAILABILITY FACTORS:

VARIABLE	ATMOSPHERIC-LOADS KG/KM2-YR	CV	AVAILABILITY FACTOR
1 CONSERV	.00	.00	.00
2 TOTAL P	30.00	.00	1.00
3 TOTAL N	.00	.00	.00
4 ORTHO P	.00	.00	.00

```
 5 INORG N          .00      .00          .00

GLOBAL INPUT VALUES:
PARAMETER                          MEAN     CV
PERIOD LENGTH      YRS            1.000   .000
PRECIPITATION M                    .700   .000
EVAPORATION    M                  1.000   .000
INCREASE IN STORAGE M            -.500   .000

TRIBUTARY DRAINAGE AREAS AND FLOWS:
ID TYPE SEG NAME              DRAINAGE AREA    MEAN FLOW  CV OF MEAN FLOW
                                       KM2       HM3/YR
 1   1    1 Stream A                380.000     1014.000        .000
 2   1    2 Stream B                100.000      300.000        .000
 3   1    3 Stream C                 50.000      150.000        .000
 4   4    3 Stream D                570.000     1430.000        .000
 5   6    3 Exchange                   .000     2000.000        .000

TRIBUTARY CONCENTRATIONS (PPB): MEAN/CV
ID        CONSERV      TOTAL P      TOTAL N      ORTHO P      INORG N
 1       .0/ .00     60.0/ .00      .0/ .00      .0/ .00      .0/ .00
 2       .0/ .00    167.0/ .00      .0/ .00      .0/ .00      .0/ .00
 3       .0/ .00    167.0/ .00      .0/ .00      .0/ .00      .0/ .00
 4       .0/ .00      .0/ .00      .0/ .00      .0/ .00      .0/ .00
 5       .0/ .00     15.0/ .00      .0/ .00      .0/ .00      .0/ .00

MODEL SEGMENTS & CALIBRATION FACTORS:
                                          ----------- CALIBRATION FACTORS -----------
SEG OUTFLOW GROUP SEGMENT NAME        P SED  N SED  CHL-A SECCHI    HOD      DISP
 1       2     1  Upper Pool         1.00   1.00   1.00   1.00   1.00     1.000
                                CV:   .000   .000   .000   .000   .000      .000
 2       3     1  Mid Pool           1.00   1.00   1.00   1.00   1.00     1.000
                                CV:   .000   .000   .000   .000   .000      .000
 3       0     1  Near Dam           1.00   1.00   1.00   1.00   1.00     1.000
                                CV:   .000   .000   .000   .000   .000      .000

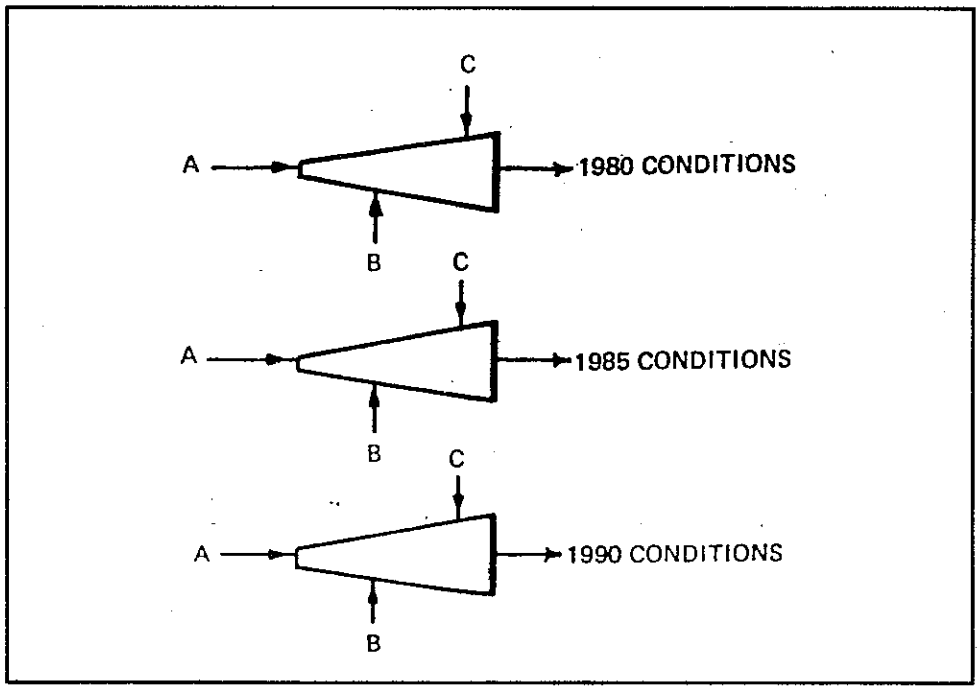
SEGMENT MORPHOMETRY: MEAN/CV
                        LENGTH      AREA  ZMEAN      ZMIX       ZHYP
ID LABEL                    KM       KM2      M         M          M
 1 Upper Pool            10.00    8.0000   8.00   6.09/ .12    .00/ .00
 2 Mid Pool              10.00   16.0000  16.00   7.87/ .12    .00/ .00
 3 Near Dam              10.00   16.0000  24.00   8.35/ .12    .00/ .00

SEGMENT OBSERVED WATER QUALITY:
SEG     TURBID CONSER TOTALP TOTALN  CHL-A SECCHI  ORG-N  TP-OP   HODV   MODV
          1/M   ---   MG/M3  MG/M3  MG/M3      M  MG/M3  MG/M3 MG/M3-D MG/M3-D
 1 MN:    .00     .0     .0     .0     .0     .0     .0     .0     .0     .0
   CV:    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00
 2 MN:    .00     .0     .0     .0     .0     .0     .0     .0     .0     .0
   CV:    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00
 3 MN:    .00     .0     .0     .0     .0     .0     .0     .0     .0     .0
   CV:    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00

CASE NOTES:
single reservoir embayment, spatially segmented
Tributary #5 (TYPE CODE=6) is used to specify  exchange between last segment and
downstream reservoir area.
```

Basic data sheet for Case 4

Single reservoir, Spatially Averaged, Multiple Load Scenario



Mass Balance Period: 1 yr

Stream Inflow Data:

Stream	Drainage Area km^2	Mean Flow hm^3/yr	Flow-Weighted Total P Concentration ppb	Scenario
A	380	1,014	60	1980 conditions
A	380	1,014	120	1985 conditions
A	380	1,014	180	1990 conditions
B	100	300	167	1980, 1985, 1990 conditions
C	50	150	167	1980, 1985, 1990 conditions

Atmospheric total P Load = 30 kg/km^2-yr

Precipitation rate = 0.7 m/yr
Evaporation rate = 1.0 m/yr
Reservoir total volume = 704 hm^3
Reservoir total surface area = 40 km^2
Reservoir total length = 30 km
Reservoir surface elevations constant

Listing of input values for Case 4

Single Reserv, 3 Scenarios

ATMOSPHERIC LOADS & AVAILABILITY FACTORS:

VARIABLE	ATMOSPHERIC-LOADS KG/KM2-YR	CV	AVAILABILITY FACTOR
1 CONSERV	.00	.00	.00
2 TOTAL P	30.00	.00	1.00
3 TOTAL N	.00	.00	.00
4 ORTHO P	.00	.00	.00
5 INORG N	.00	.00	.00

GLOBAL INPUT VALUES:

PARAMETER		MEAN	CV
PERIOD LENGTH	YRS	1.000	.000
PRECIPITATION M		.700	.000

```
EVAPORATION   M                 1.000   .000
INCREASE IN STORAGE M            .000   .000

TRIBUTARY DRAINAGE AREAS AND FLOWS:
ID TYPE SEG NAME              DRAINAGE AREA    MEAN FLOW  CV OF MEAN FLOW
                                        KM2       HM3/YR
 1   1    1 Stream A 1980          380.000      1014.000         .000
 2   1    1 Stream B 1980          100.000       300.000         .000
 3   1    1 Stream C 1980           50.000       150.000         .000
 4   1    2 Stream A 1985          380.000      1014.000         .000
 5   1    2 Stream B 1985          100.000       300.000         .000
 6   1    2 Stream C 1985           50.000       150.000         .000
 7   1    3 Stream A 1990          380.000      1014.000         .000
 8   1    3 Stream B 1990          100.000       300.000         .000
 9   1    3 Stream C 1990           50.000       150.000         .000

TRIBUTARY CONCENTRATIONS (PPB): MEAN/CV
ID        CONSERV       TOTAL P       TOTAL N       ORTHO P       INORG N
 1       .0/ .00     60.0/ .00       .0/ .00       .0/ .00       .0/ .00
 2       .0/ .00    167.0/ .00       .0/ .00       .0/ .00       .0/ .00
 3       .0/ .00    167.0/ .00       .0/ .00       .0/ .00       .0/ .00
 4       .0/ .00    120.0/ .00       .0/ .00       .0/ .00       .0/ .00
 5       .0/ .00    167.0/ .00       .0/ .00       .0/ .00       .0/ .00
 6       .0/ .00    167.0/ .00       .0/ .00       .0/ .00       .0/ .00
 7       .0/ .00    180.0/ .00       .0/ .00       .0/ .00       .0/ .00
 8       .0/ .00    167.0/ .00       .0/ .00       .0/ .00       .0/ .00
 9       .0/ .00    167.0/ .00       .0/ .00       .0/ .00       .0/ .00

MODEL SEGMENTS & CALIBRATION FACTORS:
                                      ----------- CALIBRATION FACTORS -----------
SEG OUTFLOW GROUP SEGMENT NAME       P SED   N SED   CHL-A SECCHI    HOD      DISP
 1       0     1  1980 Conditions    1.00    1.00    1.00   1.00    1.00     1.000
                                CV:   .000    .000    .000   .000    .000      .000
 2       0     2  1985 Conditions    1.00    1.00    1.00   1.00    1.00     1.000
                                CV:   .000    .000    .000   .000    .000      .000
 3       0     3  1990 Conditions    1.00    1.00    1.00   1.00    1.00     1.000
                                CV:   .000    .000    .000   .000    .000      .000

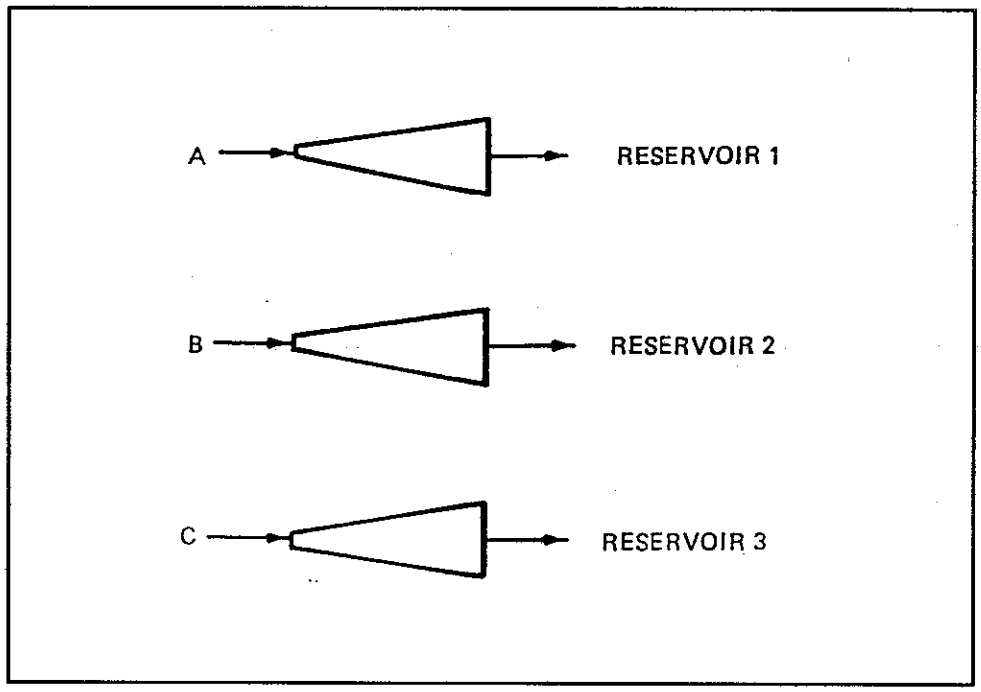
SEGMENT MORPHOMETRY: MEAN/CV
                         LENGTH      AREA  ZMEAN      ZMIX       ZHYP
ID LABEL                    KM       KM2      M         M          M
 1 1980 Conditions       30.00   40.0000  17.60   8.03/ .12    .00/ .00
 2 1985 Conditions       30.00   40.0000  17.60   8.03/ .12    .00/ .00
 3 1990 Conditions       30.00   40.0000  17.60   8.03/ .12    .00/ .00

SEGMENT OBSERVED WATER QUALITY: (none)

CASE NOTES:
single reservoir, spatially averaged
multiple load comparisons
each segment represents a different year
```

Basic data sheet for Case 5

Collection of Reservoirs, Spatially Averaged



Mass Balance Period: 1 yr

Reservoir Morphometry:

Segment	Surface Area km^2	Volume hm^3	Length km
1	8	64	10
2	16	256	10
3	16	384	10

Stream Monitoring Data:

Stream	Drainage Area km^2	Mean Flow hm^3/yr	Flow-Weighted Total P Concentration ppb
A	380	1,014	60
B	100	300	167
C	50	150	167

Atmospheric total P load = 30 kg/km^2-yr
Precipitation rate = 0.7 m/yr
Evaporation rate = 1.0 m/yr
Reservoir surface elevations constant

Listing of input values for Case 5

Collection of reservoirs

ATMOSPHERIC LOADS & AVAILABILITY FACTORS:

VARIABLE	ATMOSPHERIC-LOADS KG/KM2-YR	CV	AVAILABILITY FACTOR
1 CONSERV	.00	.00	.00
2 TOTAL P	30.00	.00	1.00
3 TOTAL N	.00	.00	.00
4 ORTHO P	.00	.00	.00
5 INORG N	.00	.00	.00

GLOBAL INPUT VALUES:

PARAMETER		MEAN	CV
AVERAGING PERIOD	YRS	1.000	.000
PRECIPITATION	METERS	.700	.000
EVAPORATION	METERS	1.000	.000
STORAGE INCREASE	METERS	.000	.000

TRIBUTARY DRAINAGE AREAS AND FLOWS:

ID	TYPE	SEG	NAME	DRAINAGE AREA KM2	MEAN FLOW HM3/YR	CV OF MEAN FLOW
1	1	1	Stream A	380.000	1014.000	.000
2	1	2	Stream B	100.000	300.000	.000
3	1	3	Stream C	50.000	150.000	.000

TRIBUTARY CONCENTRATIONS (PPB): MEAN/CV

ID	CONSERV	TOTAL P	TOTAL N	ORTHO P	INORG N
1	.0/ .00	60.0/ .00	.0/ .00	.0/ .00	.0/ .00
2	.0/ .00	167.0/ .00	.0/ .00	.0/ .00	.0/ .00
3	.0/ .00	167.0/ .00	.0/ .00	.0/ .00	.0/ .00

MODEL SEGMENTS & CALIBRATION FACTORS:

SEG	OUTFLOW	GROUP	SEGMENT NAME		P SED	N SED	CHL-A	SECCHI	HOD	DISP
					---------- CALIBRATION FACTORS ----------					
1	0	1	Reservoir 1		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
2	0	2	Reservoir 2		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000
3	0	3	Reservoir 3		1.00	1.00	1.00	1.00	1.00	1.000
				CV:	.000	.000	.000	.000	.000	.000

SEGMENT MORPHOMETRY: MEAN/CV

ID	LABEL	LENGTH KM	AREA KM2	ZMEAN M	ZMIX M	ZHYP M
1	Reservoir 1	10.00	8.0000	8.00	6.09/ .12	.00/ .00
2	Reservoir 2	10.00	16.0000	16.00	7.87/ .12	.00/ .00
3	Reservoir 3	10.00	16.0000	24.00	8.35/ .12	.00/ .00

SEGMENT OBSERVED WATER QUALITY:

SEG		TURBID 1/M	CONSER ---	TOTALP MG/M3	TOTALN MG/M3	CHL-A MG/M3	SECCHI M	ORG-N MG/M3	TP-OP MG/M3	HODV MG/M3-D	MODV MG/M3-D
1	MN:	.00	.0	.0	.0	.0	.0	.0	.0	.0	.0
	CV:	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
2	MN:	.00	.0	.0	.0	.0	.0	.0	.0	.0	.0
	CV:	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
3	MN:	.00	.0	.0	.0	.0	.0	.0	.0	.0	.0
	CV:	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

CASE NOTES:
collection of reservoirs

spatially averaged

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Appendix A
Installation

The programs require an IBM-compatible PC with at least a 286 processor, a math co-processor, and 3 megabytes of disk storage. At least 530 kilobytes of conventional memory must be available for the programs to run.

Installation is initiated by inserting the distribution diskette in an appropriate floppy drive and entering the following command:

>install c:

Note that drives other than **c:** may be substituted and that a parent directory can be established (e.g., **c:\models**). The installation program creates destination directories for each set of program files and installs files to appropriate directories. For instance, after issuing the command **install c:**, the following occurs:

FLUX files are installed in directory **c:\flux**
PROFILE files are installed in directory **c:\profile**
BATHTUB files are installed in directory **c:\bathtub**

Assistance in the acquisition and implementation of the software is available by contacting:

Dr. Robert H. Kennedy
Environmental Laboratory
USAE Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Phone: (601) 634-3659
Fax: (601) 634-3713
E-mail: webmaster@limnos.wes.army.mil

Software and update messages are also available on the Internet:

http://limnos.wes.army.mil/software/

Appendix B
Conversion Factors

To obtain values expressed in units of	Multiply units expressed in	By
Concentration	grams/cubic meter (gm/m^3)	1.000×10^3
milligrams/cubic meter (mg/m^3)	micrograms/liter (μg/ℓ)	1.000
	milligrams/liter (mg/ℓ)	1.000×10^3
	parts/billion (ppb)	1.000
	parts/million (ppm)	1.000×10^3
	pounds/gallon (lb/gal)	1.198×10^8
Flow	acre-foot/day (acre-ft/day)	4.502×10^{-1}
cubic hectometers/year (hm^3/year)	cubic feet/second (ft^3/s)	8.931×10^{-1}
	cubic meters/second (m^3/s)	3.154×10^1
	million gallons/day (mgd)	1.382
Area	acres (acres)	4.047×10^{-3}
square kilometers (km^2)	hectares (ha)	1.000×10^{-2}
	square feet (ft^2)	9.294×10^{-8}
	square meters (m^2)	1.000×10^{-6}
	square miles	2.590
Depth	feet (ft)	3.048×10^{-1}
meters (m)	inches (in.)	2.540×10^{-2}
Volume	cubic meters (m^3)	1.000×10^{-6}
cubic hectometers (hm^3)	acre-foot (acre-ft)	0.1234×10^{-2}

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Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.
A copy of the FLUX, PROFILE, and BATHTUB software is provided on the enclosed diskette.

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13. ABSTRACT *(Maximum 200 words)*

Eutrophication has several direct and indirect effects on reservoir water quality and uses. The report documents assessment procedures which have been developed for application to Corps of Engineers reservoirs. Study phases include problem identification, data gathering, and model implementation. Three computer programs are designed to assist in the last two phases:

a. FLUX—estimation of tributary nutrient loadings from grab-sample concentration data and continuous flow records using a variety of calculation methods which permit quantification of potential errors and evaluation of alternative sampling program designs.
b. PROFILE—display and reduction of pool water quality data, including calculation of hypolimnetic oxygen depletion rates, characterization of spatial and temporal variability, and robust statistical summary of mixed-layer concentration data.
c. BATHTUB—implementation of nutrient balance models and eutrophication response models in a spatially segmented hydraulic network which accounts for advective transport, diffusive transport, and nutrient sedimentation.

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Eutrophication-related water quality conditions (expressed in terms of total phosphorus, total nitrogen, chlorophyll *a*, transparency, organic nitrogen, particulate phosphorus, and hypolimnectic oxygen depletion rate) are predicted using empirical relationships which have been calibrated and tested for reservoir applications. Based upon research using several independent data sets, previous northern-lake-based empirical modeling approaches have been modified to account for effects of (a) nonlinear nutrient sedimentation kinetics; (b) algae growth limitation by phosphorus, nitrogen, light, and flushing rate; (c) inflow nutrient partitioning (bioavailability of dissolved versus particulate loadings); (d) seasonal variations in loadings and morphometry; and (e) spatial variations in nutrients and related trophic state indicators.

To reflect input data limitations and inherent model errors, inputs and outputs can be expressed in probabilistic terms. The segmented model can be applied to single reservoirs (mixed or spatially segmented), partial reservoirs (embayments, separate tributary arms), networks of reservoirs (hydrologically linked), or collections of reservoirs (hydrologically independent). The last type of application permits regional comparative assessments of reservoir conditions, controlling factors, and model performance. This instructional report describes use of PC-DOS versions of the software and follows a four-report series describing database development, model testing, model refinements, and application procedures for earlier versions of these programs.