

A Dynamic One-Dimensional Model of Hydrodynamics and Water Quality

EPD-RIV1

Version 1.0

**User's
Manual**



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Preface

This report serves as a user's manual and application guidance document for the dynamic riverine water quality model, EPD-RIV1. This model is based upon the CE-QUAL-RIV1 model developed by the U.S. Army Engineers Waterways Experiment Station (WES). The first draft of the user documentation for CE-QUAL-RIV1 was prepared by Drs. Keith W. Bedford, Robert M. Sykes and Charles Libicki of Ohio State University, as was the original version of the model code. The Version 2.0 user documentation for CE-QUAL-RIV1 resulted from revisions to the 1990 user's manual and reflected modifications made between 1990 and 1995. Revisions to the manual were made by Dr. D.M. Griffin, Louisiana Tech University, and Dr. James L. Martin and Tim Wool of AScl Corporation. Revisions were also made by Dr. Mark Dortch and Ms. Toni Schneider of the Water Quality and Contaminant Modeling branch, WES. Much of this report was extracted from the Version 2.0 documentation for that model.

The modifications to CE-QUAL-R1 resulting in the EPD-RIV1 modeling system were designed by Dr. Roy Burke III, Georgia Environmental Protection Division (EPD) of the Georgia Department of Natural Resources, and Dr. Jim Greenfield, U.S. Environmental Protection Agency (EPA). Mr. Robert Olson of NRE Inc. also contributed to the design and testing of code modifications. Revisions to the code were made by Dr. James Martin and Tim Wool of AScl Corporation.

This report was developed for Dr. Roy Burke III, Program Manager, Georgia EPD and Dr. Jim Greenfield, U.S. EPA. The manual was prepared by AScl Corporation under subcontract to NRE, Inc., Bob Olson, Project Manager.

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1. EPD-RIV1 User's Guide and Documentation for Release Version 1.0

1. Model Overview

EPD-RIV1 is a one-dimensional (cross-sectionally averaged) hydrodynamic and water quality model. It consists of two parts, a hydrodynamic code which is typically applied first, and a quality code. The hydraulic information, produced from application of the hydrodynamic model, is saved to a file which is read by, and provides transport information to, the quality code when performing quality simulations. The quality code can simulate the interactions of 16 state variables, including water temperature, nitrogen species (or nitrogenous biochemical oxygen demand), phosphorus species, dissolved oxygen, carbonaceous oxygen demand (two types), algae, iron, manganese, coliform bacteria and two arbitrary constituents. In addition, the model can simulate the impacts of macrophytes on dissolved oxygen and nutrient cycling. The model was designed for the simulation of dynamic conditions in rivers and streams for the purpose of analyzing existing conditions and performing waste load allocations, including allocations of Total Maximum Daily Loads (TMDLs). This document describes the capabilities of the model and provides guidance in assembling data required to run the model.

2. Model Background

2.1. Past

The model that serves as the basis for EPD-RIV1 was originally developed at Ohio State University at the request of the U.S. Environmental Protection Agency (EPA) for the purpose of predicting water quality associated with storm water runoff. Researchers at the U.S. Army Engineer Waterways Experiment Station (WES) were attracted to the model because it was fully dynamic for determining flow and water quality and it had several desirable numerical features, such as a two-point fourth-order scheme for accurately predicting the advection of water quality concentrations. The WES contracted Ohio State University

to modify the model code to handle control structures. This modification, along with the unsteady flow feature, gave the model the versatility needed for simulating Corps of Engineers regulated stream/waterway projects. Subsequently, the updated version was tested at WES, and additional modifications and corrections were made, resulting in Version 1.0 of CE-QUAL-RIV1, released in 1991. WES further modified and supported CE-QUAL-RIV1, releasing Version 2.0 of the model in 1995 (Environmental Laboratory 1995).

At the onset of the Chattahoochee River Modeling Project (CRMP), the Environmental Protection Division (EPD) of the Georgia Department of Natural Resources initiated a review of available models applicable to predicting the dynamics of the Chattahoochee River, Georgia, and other Georgia rivers and streams. This effort provides a platform for conducting the required studies for establishing waste load allocations, including the analyses required for establishing total maximum daily loads (TMDL). Specific candidate models were identified. Then, following identification of the technical issues the model was expected to address, an initial screening was conducted in order to identify a subset of models with greatest potential applicability. The screening was accomplished through a review of model documentation, interviews with model experts, and, in some cases, a review of computer codes. Finally, the remaining candidate models were reviewed in greater detail and a final recommendation made. The model selected for application use in the CRMP was CE-QUAL-RIV1.

Although CE-QUAL-RIV1 was considered the optimal model for application to the Chattahoochee River, there were several areas identified where the revision of the existing computer code, or development of new code, was required to (a) simulate processes in the Chattahoochee River, or (b) aid in the application of the model by making it easier to input data to the model and interpret its output. An extensive model development effort was undertaken, resulting in the software described in this series of documents and the modified version of CE-QUAL-RIV1, referred to as the EPD-RIV1.

2.2. Present

The present version of EPD-RIV1 is the result of a series of modifications to the original code to improve its performance and add to its capabilities,

particularly for performing wasteload allocations. Considerable effort has also been made to make the model easier to use. Development efforts have resulted in a series of software programs of which EPD-RIV1 is a part, and include:

- Computer System Shell
- Pre-Processor
- Deliberator
- Post-Processor, and
- Pre-Run

The capabilities and use of each of the above programs is described elsewhere in this documentation series, while this user's manual deals with the EPD-RIV1 model. A water resource database was also developed as part of the system, which is described separately. While each piece of the modeling system can be run separately, combined they provide the users with a unique set of tools to aid in analyzing environmental data, preparing data for a model application, simulating the impact of time-varying point and non-point sources on the hydrodynamics and water quality of a stream or river, and analyzing model results.

2.3. Future

Although the EPD-RIV1 model, and its supporting software, is a powerful set of tools, it will continue to evolve as the state-of-the-art advances, both in terms of environmental modeling and computer capabilities. New enhancements and modifications will be reflected in user updates and periodically documentation will be updated.

3. Capabilities and Limitations

3.1. Model Features

EPD-RIV1 is a one-dimensional (cross-sectionally averaged) model, meaning that the model resolves longitudinal variations in hydraulic and quality characteristics and is applicable where lateral and vertical variations are small. EPD-RIV1 consists of two parts, hydrodynamic and water quality. Each of these parts is a separate computer code (RIV1H, the Hydrodynamic code and RIV1Q, the water Quality code). The hydrodynamic code is applied first to predict water transport and its results are written to a file which is then read by the quality model. It can be used to predict one-dimensional hydraulic and water quality variations in streams and rivers with highly unsteady flows, although it can also be used for prediction under steady flow conditions.

Hydrodynamics: EPD-RIV1H predicts flows, depths, velocities, water surface elevations and other hydraulic characteristics. The hydrodynamic model solves the St. Venant equations as the governing flow equations using the widely accepted four-point implicit finite difference numerical scheme.

Water Quality: The quality model can predict variations in each of sixteen state variables:

- 1) Temperature
- 2) Carbonaceous Biochemical Oxygen Demand (CBOD)
- 3) CBOD2 (second CBOD type)
- 4) Nitrogenous Biochemical Oxygen Demand
- 5) Organic Nitrogen
- 6) Ammonia Nitrogen
- 7) Nitrate + Nitrite Nitrogen

- 8) Dissolved Oxygen
- 9) Organic Phosphorus
- 10) Phosphates
- 11) Algae
- 12) Dissolved Iron
- 13) Dissolved Manganese
- 14) Coliform bacteria
- 15) Arbitrary Constituent 1
- 16) Arbitrary Constituent 2

In addition, the impacts of macrophytes can be simulated. Numerical accuracy for the advection of sharp gradients is preserved in the water quality code through the use of the explicit two-point, fourth-order accurate, Holly-Preissman scheme.

Multiple Branches and Control Structures: EPD-RIV1 is capable of simulating multiple branches, and in-stream hydraulic control structures such as run-of-the-river dams, waterway locks and dams, and reregulation dams. Reaeration over dams can be simulated.

Flexible Geometry Specification: Each branch is further subdivided into nodes or cross-sections. The shape of the cross-section can be specified using simple geometric equations or look-up tables.

Flexible Time Series Input: In EPD-RIV1, all time varying data are input in the format year, month, day, and hour. Time varying data files may contain data for any period of time and the model will select the appropriate data based upon the start and end time specified for the simulation. In addition, the start and end times for the quality model do not have to be equal to those of the hydrodynamic simulation (although they must be within their range). In addition:

- A time series of computational time steps may be specified so that the user may vary the time step depending upon the dynamics of particular periods.

- The frequency at which the model writes output results can be controlled by the user.
- The values in the individual time series may be linearly interpolated between update times, at the option of the user. The user may also elect to have the values remain constant between update times (a step function). The option is available for time-varying boundary conditions, meteorological data, lateral inflows, withdrawals, and power plant discharges.

Time Varying Boundary Conditions: Boundary information is specified in separate files containing both hydraulic and quality conditions. The boundary conditions for the hydrodynamic model can be either flows or stages at the upstream boundary, or flows stages or a rating curve at the downstream boundary. Constituent concentrations are provided as boundary conditions for the quality model.

Time Varying and Constant Lateral Inflows: The model can simulate the impact tributaries not modeled in the network and point and non-point sources by adding their flows and constituent loadings as a lateral inflow. Flows and concentrations are specified which can be constant or time-varying, or a combination of both.

Time Varying Withdrawals: The model can simulate the impact withdrawals or diversions, where the user specifies the location and a time-series of the withdrawal rates.

Power Plant Discharges: EPD-RIV1 allows the user to specify power plant flows and temperatures. These discharges are only assumed to impact predicted temperatures and essentially add a heat load, computed from the flow rate and effluent temperature. The user may elect to specify a temperature of the power plant discharge or an increase in temperature above the ambient water temperatures.

Outputs: The model provides considerable flexibility as to the type and frequency of outputs. The model allows viewing simulation results during the course of the simulation, as well as writing the results to files, and the users can stop the simulation if they so choose. The users can elect not to write hydraulic output to the water quality linkage file, for example during

initial simulations with the hydrodynamic model. The users can have the model write out the time and values whenever time-varying data are updated, if they choose to. The users can also elect to have information output for only selected nodes. The users can select the frequency at which information is output to files which can be viewed by the graphical post-processor.

3.2. Model Limitations

3.2.1. Theoretical

3.2.1.1. HYDRODYNAMICS AND TRANSPORT

In the application of EPD-RIV1 it is assumed, for modeling purposes, that the waterbody is one-dimensional (longitudinal). That is, velocities are assumed to be adequately represented by an average value over the cross-section and mixing in the lateral and vertical dimensions is assumed to be sufficient to preclude the establishment of strong gradients, allowing the assumption of homogeneity in the cross-section. The remaining source of variability is then in the longitudinal dimension. The assumption of homogeneity over the cross-section is rarely completely true. Materials discharged into a river may not completely mix for some distance downstream, making the one-dimensional assumption inappropriate in the regions where complete mixing has not occurred. Some slow moving waterbodies may stratify. While the assumption of cross-sectional homogeneity is often a good approximation, it is left to the users to determine whether this assumption is valid for their particular application.

3.2.1.2. WATER QUALITY

The water quality algorithms for the conventional pollutants simulated by EPD-RIV1Q are relatively comprehensive, in comparison with other available water quality models. However, there are a number of processes not simulated by the model. For example, the model does not include sediment transport processes such as scour and deposition and their impact on water quality. Additionally, the model does simulate processes in the sediments affecting rates of oxygen demand and nutrient releases. Instead, these rates are specified to the model. The users should determine if there are processes impacting water quality which are unique to their particular system to determine if the routines included in this model are adequate.

3.2.2. Numerical

3.2.2.1. SOLUTION SCHEME

The numerical solution scheme used by both the hydrodynamic and quality models are robust. However, there may be situations where the solution scheme used in the hydrodynamic model will not converge on a stable solution. The model may also predict negative depths due to phase errors, particularly at the leading edge of a storm wave. These errors can usually be corrected by smoothing (see Troubleshooting the Hydrodynamics). The hydrodynamic model may run for some cases where the quality model will not, or will produce mass balance errors. This may also often be corrected (see Troubleshooting the Water Quality). However, for situations where the models run yet they produce unreasonable answers, it is up to the user to recognize that there is a problem and effect a solution.

3.2.2.2. COMPUTER LIMITS

While both the hydrodynamic and water quality components of EPD-RIV1 use efficient solution schemes, computer efficiency places limits on model applications in terms of computer memory and the time required to perform a simulation. For example, it is common that several hundred simulations be conducted over the course of a model application. Continuous simulations for relatively long time periods (months to years) may also be required in many applications. As the time required for a typical simulation increases, the practicality of the model decreases. The files created during the course of the simulation may also become large. The user may want to keep multiple files open (not archived) during calibration or during the application of the model in the wasteload allocation process. Thus, large amounts of storage space need to be available. The need for speed and memory is a resource issue that should be evaluated and addressed prior to applying the model. Additional information on computer requirements is provided elsewhere in this documentation.

3.2.3. Input Data

While the availability of input data is not a limitation of the model itself, it does place limits on the application of the model. For example, if in-

stream data are not available for comparison with model predictions, the model's accuracy can not be assessed. If time-variable data are not available for model forcing functions (e.g. boundary conditions, lateral inflows, meteorological conditions, etc.), or only available infrequently, then the model may not accurately predict in-stream time-variable conditions. The assembly, including analysis, of supporting data is the single most important, and time consuming, part of any model application.

4. Model Application: Hydrodynamics

4.1. Overview of Solution of Hydrodynamic Equations

The hydrodynamic component of CE-QUAL-RIV1 (RIV1H) was designed to simulate flows in river systems under highly unsteady flow conditions. In order to do so, the hydrodynamic model is based on the full (non-linear) flow equations. The basic equations solved by RIV1H are those for the:

- **conservation of momentum:** a statement that the time rate of change of momentum of a volume of water plus the net rate of efflux of momentum through that volume is equal to the net force acting upon it, and;
- **continuity:** a statement of the conservation of water mass, which in RIV1H includes a term for lateral inflows.

The net forces in the momentum equation include the forces due to:

- **gravity** acting upon the water mass,
- **friction** applied by the river bottom and channel sides, and
- **pressure** force due to the water slope.

In addition to these major forces, there are also some minor forces included in the equations solved by RIV1H. These minor forces allow simulation of the impacts of channel constrictions, such as due to bridges, through a constriction coefficient, and non-uniformities in velocities across the width of the river, such as in bends, using a momentum correction

coefficient. The following equations govern the unsteady, 1-D (longitudinal) hydrodynamics and transport:

Continuity

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$$

Equation 4-1

Momentum

$$\frac{\partial Q}{\partial t} + \frac{\partial(UQ)}{\partial x} + gA \frac{\partial h}{\partial x} = gA \left(S_o - S_f - \frac{h_E}{\Delta x} \right) + qU_q$$

Equation 4-2

where:

Q	= flow rate
U	= velocity
q	= lateral inflow rate per unit river length
U _q	= velocity of lateral inflow
A	= area
h	= depth
g	= gravitational acceleration
S _o	= bottom slope
S _f	= friction slope
x	= longitudinal distance
t	= time
h _E	= head loss

Equation 4-1 and Equation 4-2 are commonly referred to as the St. Venant equations. The equations are solved assuming that:

- Lateral and vertical gradients are small and can be neglected; thus the equations are cross-sectionally averaged for flow and constituent variables (1-D assumption).
- All cross sections and bottom configurations are known.

- All lateral point and non-point source flows and input concentrations are known.

When solved, the hydraulic transport equations permit the calculation of downstream histories of flow and water surface elevation.

4.2. Schematic of Hydrodynamic Model

The EPD-RIV1H solves the hydrodynamic equations to provide time histories of flows and water surface elevation. Since there is no analytical solution to the governing equations, they must be solved numerically. The solution scheme used in RIV1H is the widely known and accepted four-point implicit solution technique. The method was first used by Preissmann (1961) and is probably the most accepted and successful procedure used today. It is also called a box scheme (Figure 4-1), where n refers to time and j to space. The space derivatives and function values are evaluated at an interior point of the box $(n+\theta)\Delta t$, and terms of $(n+1)\Delta t$ enter all of the equations. The result is a system of equations that must be solved simultaneously. Since, as stated above, all of the non-linear terms are retained, then the system of equations must be solved iteratively at each step time. An initial estimate is made and then the equations solved and results compared to the estimate. If they are acceptable (within some criteria to test for convergence), then the solution proceeds to the next time step, otherwise another iteration is made. Thus, the solution is controlled in part by information provided by the user, including the:

- time step,
- converge criteria, and
- weighting factor (θ)

The number of iterations allowed is presently set in the code to 200. If the model does not converge on a solution within 200 iterations, it will stop and write out diagnostic messages.

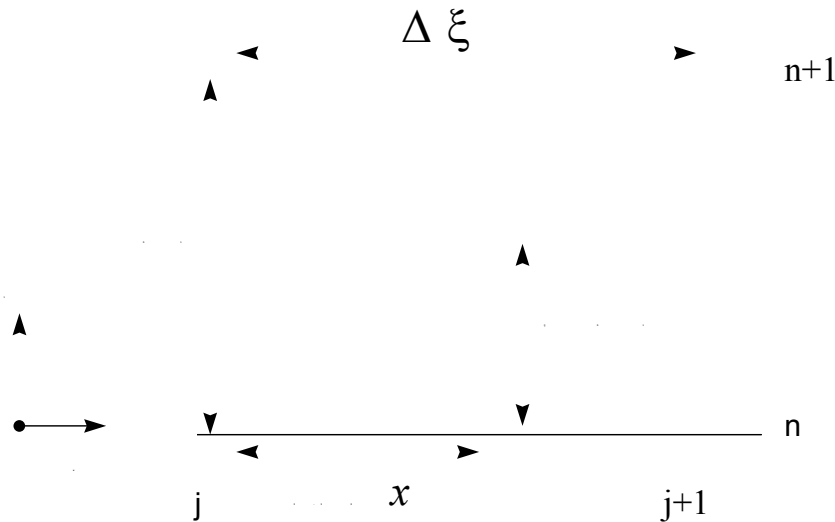


Figure 4-1 Four Point Implicit Solution Technique

The solution method (as determined by a Von Neumann stability analysis by Fread, 1974, and Liggett and Cinge, 1975) is unconditionally stable (theoretically) for $0.5 < \theta < 1.0$, and permits relatively unequal space and time-steps. The scheme has second-order accuracy when $\theta = 0.5$ and first-order accuracy when $\theta = 1.0$. It is unstable for $0.5 > \theta$. In practice other factors may also contribute to the instability of the solution scheme. The factors include dramatic changes in the channel cross-sectional properties, abrupt changes in the channel slope and characteristics of the flood wave itself. Thus, any model application should include an analysis of the sensitivity of the accuracy of the solution to various time and distance intervals (Barkau 1995).

The solution technique is implemented on a river system that has been discretized by a network of time and space nodes separated by time and space increments Δt and Δx . For example, the users must determine the distance between nodes. Then, for each node they must apply information about the cross-sectional shape, roughness, bottom elevation, and initial conditions (the starting point for the first iteration) for flow and depth.

The model is driven then by information specified at the boundaries of the discretized grid (the boundary conditions). Some of the other factors impacting the solution include:

- **Lateral and tributary inflow:** runoff from lands adjacent to the channel, point sources, or tributary inflow which can cause increased levels of total mass and momentum in the river
- **Channel constrictions.** Often very intense channel constrictions, due to bridges for example, occur over channel lengths that are far too small to economically resolve in the model. The effect of such constrictions is a momentum loss and backwater effect, accounted for in the momentum equation by subtracting a force term, based upon a user specified coefficient, K_E used in computing the head loss from

$$h_E = \frac{K_E}{2g} \left(\frac{Q}{A} \right)^2$$

Equation 4-3

The default value is zero for no constriction loss. A value for K_E as high as 0.5 may be appropriate for an abrupt constriction.

- **Non-uniform velocities.** When the velocity across the channel is substantially non-uniform through the model reach (such as in sharp bends), it may be necessary to use a momentum correction factor β in the momentum equation. The momentum correction factor β permits the use of the average velocity in the solution whereas the velocity distribution at each cross section may be quite different from the average. The default value of 1.0 is recommended for rivers and streams.
- **Tributary networks.** The momentum and continuity equations above must be applied to each and every tributary entering the main stem. At each junction, the water surfaces in each branch must be equal. These are "internal boundaries" and are computed by the model.
- **Boundary conditions.** The solution requires that boundary conditions be specified for the upstream boundary ($x = 0$) and the downstream boundary ($x = L$). The upstream boundary can be either flows or depths. The downstream boundary may be flows, depths, or a rating curve. It should be noted that the

upstream boundary condition for a tributary can be selected by specifying either the elevation or the flow. At the downstream tributary boundary, i.e. the confluence with the main stem, only the elevation is allowed as a "internal boundary" condition to ensure that continuity is preserved at the junction. Internal boundaries are computed by the model and not specified by the user.

Given the above information, then the model will step through time, over a period specified by the user, and compute a time history of downstream flows and water surface elevations.

4.3. Data Preparation

One of the first tasks associated with a model application is the assembly of the input data. This is a major task and may account for by far the majority of the time and resources required for a model application. The data required are those necessary to configure the model for a particular system (geometric data), provide forcings to the model such as boundary conditions and lateral inflows, and evaluate the model's performance.

4.3.1. Geometric Data

4.3.1.1. MODEL GRID

One of the first tasks associated with preparing input for EPD-RIV1 is assembling the geometric data. These data will be used to define the characteristics of the waterbody and the computational grid used to represent it. In RIV1, the waterbody is mapped onto a network consisting of one or more branches. A branch is defined as a stretch of river whose boundaries are a system boundary, a receiving stream, or a control structure. For example, the branches may represent the main stem river and its tributaries, or may represent lengths of the river which are separated by a control structure such as a dam. Each branch is then further subdivided into nodes, or locations in the river with known cross-sectional characteristics which are separated from each other by a known distance. The length between nodes, or cross-sections, may vary but that variation should be gradual to minimize discretization errors. For example,

abrupt changes in cross-sectional area, roughness, lengths, etc. may cause stability problems in both the hydrodynamic and quality model.

Factors affecting the computational grid. A number of factors must be evaluated and weighed against each other when setting up the computational grid. These include:

- **Boundary Conditions:** The computational grid must be set up so that the upstream boundary conditions, for both the hydrodynamic (e.g. flows) and water quality model (e.g. constituent inflow concentrations), are known and well characterized. A common practice is to locate a boundary where flow or water quality data are available, such as at USGS gaging stations. It is also often best to locate model boundaries at some point of control. A "control" is a location where there is physical dependence between water surface elevation and discharge, which may be a structure, constriction, or change in bottom elevation. U.S. Geological Survey gage stations, for example, are normally established at control points in a river. Likewise, the downstream boundary must either be well characterized or sufficiently below the area of interest so that errors in its specification do not affect predictions in the area of interest. Care needs to be exercised in establishing model boundaries at areas which are not controls since unless flow is uniform the discharge is not a function of elevation alone (Henderson 1966).
- **Location of Control Structures:** If there are control structures within the system, such as dams with a controlled release, then the grid must be broken into two or more branches. Boundary conditions (such as a release) can only be specified for a branch.
- **Tributary Impacts:** In many cases the impacts of tributaries on the main river or stream can be described rather than predicted. That is the user specifies the flows and constituent concentrations for the tributary (e.g. in the lateral inflow file read by EPD-RIV1). Alternatively, if the flows in the main channel and tributary are linked in some way, or it is necessary to predict (rather than describe) the flows and quality of the tributary, then it may be necessary to include it in the modeled grid as a separate branch.

- **Travel time:** A high degree of grid resolution is required in some hydraulic studies, such as those used to evaluate flooding potential. However, the resolution required to resolve water quality gradients may be different. For example, a material that decays at a rate of 0.1 day^{-1} will lose 10 percent of its mass per day (or require approximately 7 days to lose 50 percent of its mass and 23 days to lose 90 percent). Thus, if the travel time through the entire grid is too short, it would be necessary to increase the overall length (size) of the computational grid in order to resolve the decay of the material, and its possible impact on other materials. Conversely, if the spacing between nodes within the grid is such that travel times between them are short, it may be possible to reduce the number of nodes without impacting water quality predictions.
- **Gradients:** The spacing of nodes must be sufficient to allow the model to capture gradients, in both hydraulic (e.g. depths and velocities) and water quality characteristics. In general, if the model is not capturing observed gradients, it may be necessary to increase grid resolution.
- **Resource Requirements:** The greater the number of branches and nodes, the greater the memory and computational time required to run the application and store simulation results, and the more data required to support the study. In general, it is often preferable to err on the side of greater grid resolution. However, over specifying the grid may result in unreasonable resource demands.
- **Data Defining the Computational Grid:** Once the extent of the grid has been determined, the identification and connectivity of each branch included in the computation grid is defined by specifying the following information:
 - **Branch Name:** provided for conveniently labeling the branch
 - **Branch Number:** used by the model for recognizing the branch

- **Downstream Branch:** either zero, if the branch terminates, or the number of the branch it is connected to at its downstream end
- **Downstream Node:** specification of the down-stream cross-section allows the user to connect a branch to a location other than the uppermost node of the downstream (receiving) branch. For example, if the downstream branch for branch 1 was branch 2, and the downstream node was 4, then the flows from branch 1 would enter branch 2 at node 4 rather than node 1.

If there is no branch located above the particular branch, then the model will expect an upstream boundary condition. If there is not a downstream branch, then the model will expect a downstream boundary condition. If two branches are connected, and the downstream node is zero, indicating a control structure, then the user must specify a downstream boundary condition. If the downstream node is non-zero, then the model will expect a downstream head boundary condition and the model will compute the boundary condition (an internal boundary) to insure that mass is conserved.

Once the branches have been identified, then they are further subdivided into nodes. There must be at least three nodes per branch. The information required to define the individual nodes include their:

- **Name:** provided for convenient recognition of the location of the node,
- **Bed Elevation (ft):** measured from some common datum,
- **Channel Length (ft):** the distance along the river from this node to the next node downstream.

4.3.1.2. CROSS-SECTIONAL DATA

Cross-sectional data are required to relate channel cross-sectional areas and top-widths to depth and may be specified in RIV1H using common shapes, as described by power equations, or by look-up tables of X,Y pairs. The cross-sectional data provided as look-up data are provided in a separate file from the main input to the model which contains the X and Y coordinate data. RIV1H reads the cross-section coordinate data and uses

them to generate a table of areas versus heights and widths. The model also has the capability of developing the necessary cross-sectional data for nodes where no information is available by "blending" information from the upstream and downstream cross-sections. If data are only provided for an upstream cross-section, the model assumes that the cross-section of the downstream node is identical in shape.

RIV1H allows the cross-sectional shapes to be defined by a power equation of the form of:

$$A = C_1 H + C_2 H^{C_3}$$

Equation 4-4

where A is the area (ft²), H stage (ft) and C₁ to C₃ are user supplied coefficients. This equation allows the user to describe a variety of standard shapes, including rectangles, triangles and trapezoids. For example, with C₂ = 0, they describe a rectangle of width C₁. In cases where an ellipse would give a better fit (for instance, flow in a partially full conduit), C₁ is half the vertical axis length, C₂ is half the horizontal axis length, and C₃ is set to -1 to indicate to the program that an ellipsoid description is intended. If C₁ = C₂, of course, the cross section is circular.

One common problem in idealizing cross-sectional shapes is discontinuities. Discontinuities may occur in very irregularly shaped cross sections. Discontinuities are particularly common where it is necessary to include the flood plain in computations. For such cases, it is preferable to input surveyed cross-sectional data rather than using the idealized equations described above.

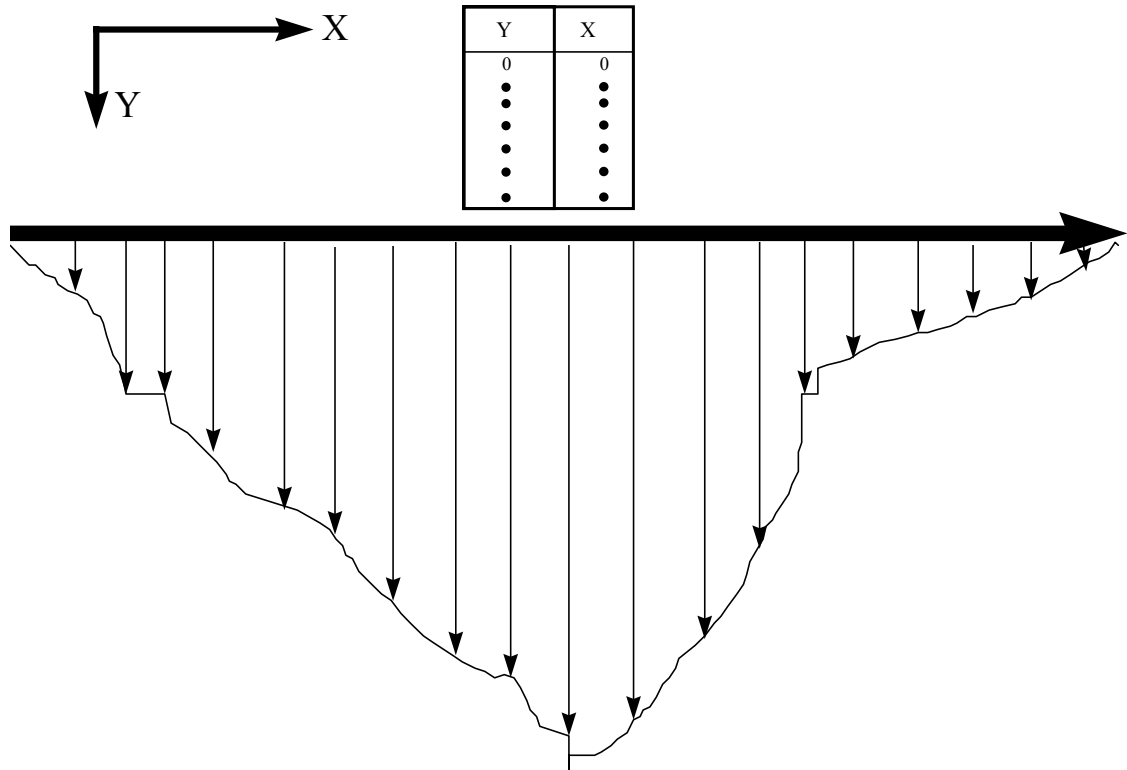


Figure 4-2

RIV1H can develop cross-sections' shapes from survey data in two ways. The simplest method develops a relationship for flow, area, and depth from a set of X,Y pairs. A second method allows for development of the necessary cross-section relationships by "blending" information from the upstream and downstream cross sections (parent cross sections). In cases where only one parent cross section exists, the computed cross section is an exact copy of the parent. If there are no parent cross sections, an error results.

RIV1H reads in the cross-section coordinate list and uses it to generate a table of area versus height and width. The algorithm used allows cross sections to be bumpy but they cannot fold in on themselves or have overhangs. The program inspects the data to make sure this is the case and writes an error message if it is not.

Each tabulated cross section is given a name, which the model uses to recognize the cross-sectional information, and a series of x and y

coordinates (in feet) with the origin for x and y beginning at the top of the left stream bank, where x increases to the right and y increases downward when looking downstream (Figure 4-2). As with the algebraic method, the channel bed elevation is understood to refer to the absolute lowest point in the surveyed cross section.

4.3.2. Initial Conditions

Initial, or start up conditions, are required by RIV1H for both flow (ft³/sec) and depth (ft). The initial flow condition is usually some steady flow, such as the base flow. The initial flow specified should also correspond to the initial flows specified in the boundary condition, lateral inflow, and withdrawal files. For example, if there is a large difference in flows between the initial conditions and those in the first updates of the forcing files, the model may become unstable. Similarly, the initial water surface elevations should reflect the conditions expected for the initial flows.

Initial depths are often difficult to estimate from field data alone, except for very simple systems, since they reflect the combined effect of the model grid, bottom roughness and model forcings (inflows and withdrawals). They may be obtained from previous hydraulic model applications, if available. Otherwise, it may be necessary to make a best estimate of the initial conditions, run the model under steady flow conditions, let the model come to an equilibrium, and then use those results as the initial conditions for subsequent simulations. If the initial estimates of depths are greatly different from the equilibrium condition, the predicted values of the hydraulic variables (flows, stages, etc) may oscillate. These results should not be used in subsequent quality predictions. If greatly different, the model may become unstable. The users must then examine the results and determine the cause (e.g. location) of the instability and refine their initial depth estimates until the model runs. See Section 4.4.5 Trouble Shooting for additional information on start up errors.

4.3.3. Model Forcing Data

4.3.3.1. BOUNDARY CONDITIONS

There are two types of boundary conditions for RIV1H: External and Internal. The Internal boundaries are computed by the model. For example, in the case of an internal boundary formed by the junction of two

tributaries, RIV1H computes the water surface elevation and it is not specified in input. External, or system, boundaries are at the ends of a branch, such as the upstream and downstream ends of the main branch. In order to solve the governing equations, a pair of boundary conditions, one upstream and one downstream, must be known at all model time steps.

Boundary condition information required by RIV1H includes, for the upstream boundary

- flows (ft^3/sec), or
- stage (ft),

and for the downstream boundary

- flows (ft^3/sec),
- stage (ft), or
- a rating curve.

For flow or stage boundary conditions the user may specify a constant boundary value. If a constant value is not specified, then the model will expect a time series of values to be read from an external file. In the boundary condition the user specifies a date (day, month and year) and time (decimal hours) for each value, and a separate file is prepared for each boundary condition. The user specifies the branch that the file contains the boundary condition for, whether it is an upstream or downstream boundary, and the type of boundary that will be used. The user also selects whether the model will linearly interpolate, or not, between boundary updates.

Boundary data are required for both the upstream and downstream boundary. As mentioned previously, in some cases it may not be critical to specify the downstream boundary as accurately if it is located sufficiently far downstream of the area of interest in the modeling study so as not to influence it. This may be possible with rivers of moderate slopes, but would almost never be the case where backwater effects occur within the area of interest. For upstream boundaries, and for cases where the downstream boundary is important, the boundaries drive the simulation

and they must be as accurate and as complete as possible. If these data are inaccurate, then the model predictions will be as well. It is a useless exercise to attempt to calibrate the model to field data when the data used to drive the model are inaccurate (Cole 1995).

Boundaries are usually located at some control point. They are also usually located where data are available. For example, USGS gages are usually located at control points (points where there is a unique relationship between flows and water surface elevations) and used for specifying boundary conditions.

The frequency at which the boundary conditions should be specified depends upon gradients. That is, how frequently and by how much do the flows change? For example, if the upstream boundary were a peaking hydropower facility, then the flows may change rapidly (so must be specified frequently) during generation and then be relatively constant between generation periods (may be specified infrequently). Where much of the inflow coming into the system through the upstream boundary is not controlled, then frequent data may be required. For example, daily averaged flows from gaging stations are usually not sufficient. Data should usually be obtained on an hourly or more frequent basis. As with the geometric data, it is usually best to err on the side of increased frequency.

If a rating curve is specified as the downstream boundary condition, it must be of the form:

$$H = COEFF \ Q^{EXPO}$$

where H is the depth of flow (ft), Q is the discharge (ft³/sec), and COEFF and EXPO are specified by the user. These curves are often available from state discharge data at gaging stations or from outfall relationships at control structures such as dams and weirs. If the available rating curve is of the form $Q = aH^b$, then simply set $EXPO = 1/b$ and $COEF = a(-1/b)$.

4.3.3.2.ROUGHNESS COEFFICIENTS

The bottom roughness is essentially a boundary condition to RIV1H and is described using a roughness coefficient referred to here as Manning's n.

Manning's n is the most commonly used means of describing bottom roughness in hydraulic and hydrodynamic models and, although empirical, is well known.

The user must estimate and provide RIV1H a value for Manning's n at each modeled node, or cross-section. A first approximation of Manning's n for a particular application can be obtained from tabulated values, such as those provided below. The user is also referred to Chow (1959), the USACE (1959) and French (1985) for extensive tables of n values as a function of channel type. The final values for a particular application are often determined during the course of model calibration.

Table 4-1. Typical values for Manning's n .

Type of Channel and Description	Minimum	Normal	Maximum
A. Natural Streams (top width at flood stage < 100ft)			
1. Streams on plain			
a. Clean, straight, full stage, no rifts or deep pools	0.025	0.03	0.033
b. Same as above but more stones and weeds	0.03	0.035	0.04
c. Clean, winding, some pools and shoals	0.033	0.04	0.045
d. Same as above but some weeds and stones	0.035	0.045	0.05
e. Same as d but lower stages, more ineffective slopes and section	0.04	0.048	0.055
f. Same as d but more stones	0.045	0.05	0.06
g. Sluggish reaches, weedy, deep pools	0.05	0.07	0.08
h. Very weedy reaches, deep pools or floodways with heavy stands of timber and underbrush	0.07	0.1	0.15
2. Mountain Streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. Bottom with gravel, cobbles, and a few boulders	0.03	0.04	0.05
b. Bottom with cobbles and large boulders	0.04	0.05	0.07
B. Major Streams (top width at flood stage > 100 ft) (Note: the n value is less than that for similar minor streams since banks offer less effective resistance.			
a. Regular section with no boulders or brush	0.025		0.06
b. Irregular and rough	0.035		0.1

While it would be ideal to consider the Manning's n constant for a particular river channel, in reality the roughness is highly variable. For example, the value may vary with the depth of flow as different surfaces come into contact with the water. High values may be more representative for shallow-depth conditions whereas lower values may be appropriate for deeper flow. For example, shoal areas exhibit a variable n that can have a significant effect on computed stage; at low stage, n is usually larger than at high stage.

For time-varying flow conditions, a variable Manning's coefficient may have to be adjusted as a function of depth during the simulation. RIV1H allows the user to vary n using the equation

$$n = a - b * H$$

Equation 4-5

where a and b are user supplied coefficients for each node and H is the depth at that node. When the user initiates a simulation, the model first sets n to the input value specified for the node. As the program executes, n is adjusted with relation to depth over time. If at some point during the execution, the value of n becomes less than 0.01, n is reset to 0.01 and a message printed to the diagnostic file.

4.3.3.3. LATERAL INFLOWS

The lateral inflows specified to RIV1H include both point and non-point sources. Data required to specify the lateral inflows are flows (ft^3/sec), for the hydrodynamic model, their associated concentrations, for the quality model, and the location at which they enter the model network. There are two alternatives provided for entering lateral inflow information: constant and time-varying. The constant lateral inflows are specified along with other node information (e.g. roughness coefficients, initial conditions, etc.). The time-varying data are included as an auxiliary file. The flows from both sources are added together by the model.

If time-varying lateral inflows are specified, the user must create an auxiliary file containing a time series of flows (and concentrations for water quality simulations). The flows and concentrations may be derived from field or monitoring data or estimated by modeling. However, as with boundary conditions, the data should be as frequent and accurate as possible since they directly impact model predictions.

A relatively large number of point and non-point sources may commonly enter the modeled system. The data available from the different sources are often of varying frequencies and quality. However, to avoid the management nightmare that would result from different files for each source, and perhaps each constituent, only a single lateral inflow file may be used in a simulation. The file specifies the nodes or cross-sections at

which the lateral inflows enter and then provides a time series of their values (e.g. flows and concentrations, with only the flows being used in the hydrodynamic predictions). Therefore, prior to inputting the data to RIV1H, the lateral inflows must be processed so that all data are provided at the same frequency. The evaluation of the data and processing of the file is a major function of the DELIBERATOR, and the user is referred to its description for guidance in accomplishing this task. The node at which the inflow is specified to enter is the node number assigned by EPD-RIV1. It is suggested that the model first be run and the node numbers obtained from the output file.

The user may also enter scale and conversion factors for each node, which have default values of one. The lateral inflow values multiplied by the scale and conversion factors are used by the model. The user may also elect to have the model linearly interpolate between update intervals or not.

4.3.3.4. WITHDRAWALS

Withdrawals, where water is removed from the system, may also be specified. The withdrawal flows are specified in an auxiliary file which specifies the nodes where the withdrawals occur and a time series of the flow values (ft³/sec). As with the lateral inflows, only a single withdrawal file may be specified for a particular run. Therefore, all withdrawal flows must be specified in this single file and all must be provided at the same frequency. The DELIBERATOR may be used to synchronize multiple withdrawal rates. The user may specify scale and conversion factors for each withdrawal location, which have default values of one. The withdrawal rates multiplied by the scale and conversion factors are used by the model. The user may also elect to have the model linearly interpolate between update intervals or not.

4.3.4. Hydraulic and Control Parameters

4.3.4.1. HYDRAULIC PARAMETERS

The hydraulic parameters specified in RIV1H include the gravitational acceleration, two coefficients affecting the numerical solution, and a momentum correction coefficient. The default value of acceleration caused by gravity is set at 32.174 ft/sec² under the assumption that the units used in modeling are the customary English units. The water quality

program does not accept input data with SI units, although it converts to SI units.

The numerical method used by RIV1H is the four-point implicit method first used by Preissman (1961) with subsequent applications by, among others, Amein and Fang (1970) and Amein and Chu (1975). This formulation is currently being used by Fread (1973, 1978) in the National Weather Service Dambreak Model (Fread 1978). The method is weighted implicitly at each time level, and the weighting coefficient (THETA) is specified by the user. The method is unconditionally stable for $0.5 < \text{THETA} < 1.0$, and permits relatively unequal space and time-steps. The scheme has second-order accuracy when $\text{THETA} = 0.5$ and first-order accuracy when $\text{THETA} = 1.0$. A default value of 0.55 is cited in the literature as optimal for model accuracy; however, a higher value (i.e., 0.6 to 0.75) is often used to enhance stability. It is recommended that the user not use values outside of the range of 0.55 to 0.75.

The numerical method employed by the model uses an iterative approach to obtain a solution to the non-linear equations. A tolerance factor (TOLER) is specified by the user which the model uses to determine if the answer has converged. The user will often notice that the model runs faster when conditions are not changing, since the model requires fewer iterations to converge. A maximum of 200 iterations is allowed before the model stops execution and writes out an error message.

TOLER, is assigned a default value of 0.001. Iteration ceases when all residuals (i.e., differences in successive iterations) for flow and area are less than TOLER times the root mean square of all flows or areas in the system. Experience suggests that often a larger value (i.e., 0.1) can be used to reduce run time without substantially sacrificing accuracy.

When the velocity across the channel is substantially non-uniform through the model reach, it may be necessary to use a momentum correction factor (BETA) in the momentum equation. The momentum correction factor permits the use of the average velocity whereas the velocity distribution at each cross section may be quite different from the average. It equals 1.0 for uniform flow (whereas 1.0 is no correction) and cannot be less than 1.0. For RIV1H, a constant value is used throughout the modeled reach. The default value of 1.0 is recommended for rivers and streams.

4.3.4.2. CONTROL PARAMETERS

The control parameters include:

- Start and End Times for the Simulation
- Print Intervals, and
- Time steps.

The start and end times specify whatever period the user want to simulate. The user should make sure that there are data in the time series files (e.g. boundary conditions, lateral inflows and withdrawals) for this period.

For the print intervals, the user specifies a date and then a frequency (hours). The model will then print at that frequency until the next update. This allows the users to vary the print interval over the simulation, if they choose to do so. For example, they may want to print results more frequently during the initial start up or during storm periods.

Similarly for the model time step, the user specifies a date and time step, and that time step will be used between that date and the next specified. One advantage of the implicit scheme used by RIV1H is that the time step is not controlled by the Courant condition (see Section 4.4.5, Trouble Shooting), which results in smaller time step limits under dynamic conditions. A disadvantage of the numerical scheme is, however, that there are not well defined limits to aid the user in determining what the time step should be. Typical time steps are on the order of 15 to 30 minutes. In general, if the Froude number (a computed variable included in the model output) is greater than one, the computed flows are supercritical and the model should crash (become numerically unstable). Also, while the hydrodynamic model is not limited by the Courant number, the quality model is. So there may be situations where the hydrodynamic model will run and produce accurate results which can not be used by the quality model. Therefore, the user will want to adjust the time step (and/or distance increments) so that the Courant number (also an output variable) is less than one to avoid stability problems in the quality simulations. The user should also adjust the time or spatial steps so that the Courant number is reasonably close one to minimize phase errors. Longer time steps may be possible for relatively steady flow conditions while smaller time steps may be required under very dynamic conditions. See Section 4.4.5, Trouble Shooting, for additional information on the model time step.

4.3.5. Calibration Data

The application of RIV1 also requires that data be available to calibrate and the model and evaluate its predictions. While it is possible to apply EPD-RIV1 without the use of calibration or evaluation data, it would not be possible to estimate the uncertainty associated with that application. The data usually consist of time series of hydraulic measurements, such as

- flows
- velocities, and/or
- water surface elevations

at a series of points along the river which can be compared to model predictions, graphically and statistically. Flow measurements provide a means of checking your water balance to make sure that you are properly accounting for all of the inflows and withdrawals. Velocities are a useful check against model predictions. However, the user must remember that the model is predicting a cross-sectionally averaged velocity. Water surface elevations are most commonly used to check model predictions, to insure that the model captures the timing, duration and peak of storm waves, for example.

Another very good source of data are dye studies. Comparison with dye concentrations can be accomplished after linking RIV1H with the quality code (RIV1Q). The time-of-travel of the dye centroid provides a good check of model hydraulic predictions. The dispersion of the dye cloud provides a good check of the dispersion rates used in the quality model.

Generally, at least two sets of data are needed; often described as a set for model calibration and a second, independent, data set for model evaluation. However, this distinction is misleading since the modelers will commonly use all of the data they have available to aid in defining the system and testing the application. Ideally, the data should

- contain one or more large events, and

- contain periods of low flows,

It is usually best for the evaluation if sufficient data are available to test model capabilities under conditions different from those used in the calibration, or test the "robustness" of the application. For example, geometric or cross-sectional data that may be adequate for one flow condition may not be adequate for another; a condition that may only be detected where sufficient data are available to evaluate the model under a variety of flow conditions.

Where field studies are planned to obtain the calibration data, it is important to remember that the model predictions are only as good as the data used to drive the model. For example, it would be a useless exercise to calibrate the model when the boundary forcings are not well known. Ideally, the availability of adequate data should be assessed prior to beginning the modeling study. If sufficient data are not available, then plans should be made for obtaining them. In many cases, an iterative approach is often useful. That is, the sampling plan can be designed with the model in mind. Initial model simulations may aid in evaluating and identifying deficiencies in the data, which can be corrected in subsequent studies.

4.4. Simulations

4.4.1. Model Preparation

Once the data have been gathered, they are used to prepare input data sets for the model. The function of the Deliberator and pre-processor are to aid the user in the preparation of these files. The reader should refer to the sections dealing specifically with those programs for a detailed description of their use. The preparation begins with the creation of a **project file**. The project file contains the names and locations of the main input data sets and the auxiliary files. The files may exist or the user can create them from scratch. The files that may be used to control simulation include:

- **Main input control file** (required): contains information on the simulation period, print controls, time steps, beginning river mile, hydraulic parameters, branch names, and specification of the connectivity of branches and their boundary conditions. Then for each branch, and for each cross-section (node) within

a branch, an input screen is provided for a descriptive name of the cross-section, the name of the cross-section used in the look up tables (if used), the lengths (distance to the next cross-section), initial flows and depths, bottom elevations, constant lateral inflows, coefficients for the cross sectional area (if used instead of look up tables), depth variations in Manning's n , the momentum correction coefficient, and Manning's n .

The remainder of the files are referred to as auxiliary files. They are not required for a simulation, and are only included where needed. For example, a constant flow may be specified for the upstream boundary in the main control file. If a constant value is specified, then a boundary file is not needed. Similarly, if the cross-section shapes (areas) are specified using the area equations, a look up table is not required. Time-varying lateral inflows and withdrawals are only specified where required. The auxiliary files include:

- Lateral Inflow File (One file only):
 - ◆ locations (node numbers) receiving lateral inflow
 - ◆ interpolation option (stair-stepped or linear)
 - ◆ dates (year, month, day, decimal hour) and flows (cfs)
- Withdrawal File (One file only):
 - ◆ locations (node numbers) for the withdrawal
 - ◆ interpolation option (stair-stepped or linear)
 - ◆ dates (year, month, day, decimal hour) and withdrawal flows (cfs)
- Boundary Condition File (Separate files for each boundary condition):
 - ◆ branch to which boundary applies
 - ◆ interpolation option (stair-stepped or linear)

- ◆ dates (year, month, day, decimal hour) and flows (cfs) or depths (ft)
- Cross-Sectional File
 - ◆ names of cross-section
 - ◆ y-x pairs of cross-sectional data

4.4.2. Model Simulations

Once the input files are prepared, and the project file completed, the users should return to the SHELL and select the project (Figure 4-3). The users

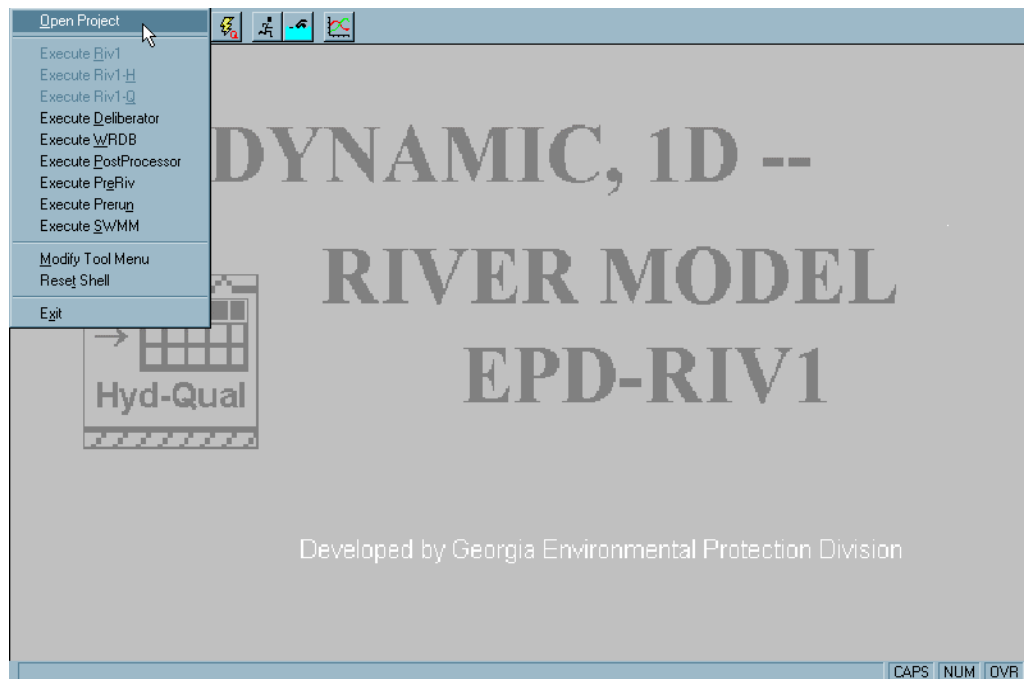


Figure 4-3

can then execute the model from either the file menu or by clicking on the run icon for H (RIV1H). Before the model executes, the users will have to respond to three questions:

- 1) Do you want to create a report ?
- 2) Do you want to write a hydrodynamic linkage file?

3) Do you want to write out time-varying data?

If the users say yes to the first question, they can fill out a form which documents the simulation (Figure 4-4). Additional information describing the input files, control information, and length of simulation will be

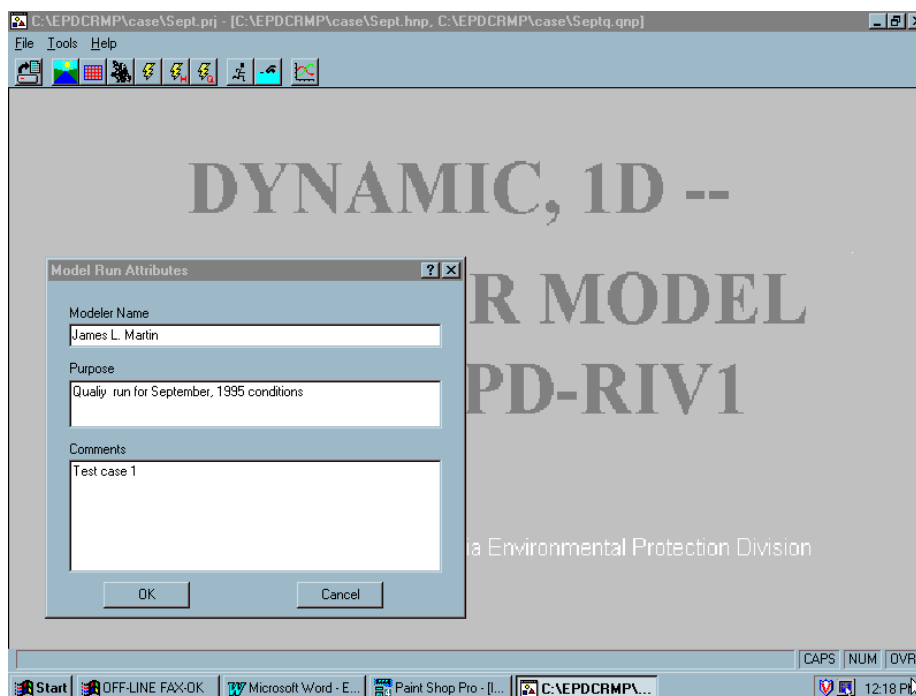


Figure 4-4

appended to the information the users provide. The users can then save the file at the end of the simulation.

If the users say no to the second question, no hydrodynamic linkage file will be created. Since this file may become large and writing to it takes time, not electing to create it will save both disk space and simulation time. For example, the users may not want to write this file during their initial hydrodynamic simulations. It is of course required to have this file if they then want to run the quality model.

If the users say yes to the third question, then information will be written to the output file each time that time-varying information is updated from the auxiliary files. This is usually only needed to aid in diagnosing errors.

After these questions have been addressed, the model will execute. During execution, intermediate model results will be displayed (Figure 4-5). The user may scroll through the model nodes or through the display variables. If the users encounter a problem that they need to correct, that may stop the program. Also, the priority of the job may be changed during the simulation. The users may pause (stop) the simulation if they need to do something else or may maximize the priority by putting the model in turbo mode. The fastest run times will occur if they shut off the writing of the intermediate simulation results and turn the model to turbo.

Once the simulation is complete, the grid will disappear and they will be back in the shell. If the users created a report, they will be asked to save it at this time. The users may then view the output files or graph the simulation results.

4.4.3. Model Output

The output from the model includes the intermediate screen results and the simulation report. Additional files created that the users can view include:

- **Output File:** This file mimics the input. When created, it will have the same name as the master input file but with the extension *.OUT. It contains much of the same information as the report prepared by the pre-processor. In addition, there are diagnostic messages which are written to this file. It is a text file that must be examined by an editor or word-processor (for convenience the users should put their favorite editor on the tool menu in the SHELL).

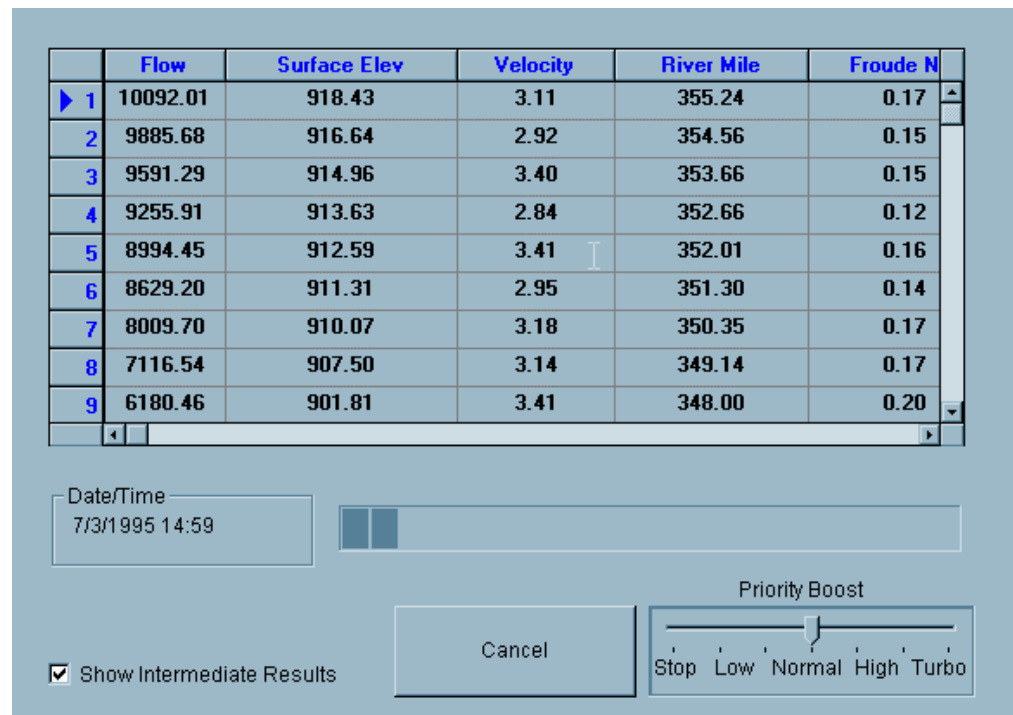


Figure 4-5

- **Graphics File:** A graphics file will be created with the same name as the master input file but with the extension *.BMD. The graphics file is used by the post-processor and contains the same result information as is written to the screen during runtime. The output includes both variables that are computed as part of the model solution (e.g. flows and water surface elevations) and those intended to aid the user in evaluation of the model results (e.g. Froude and Courant numbers). The following information is written to the file at the frequency specified by the user for each selected model node:
 - Flow (cfs)
 - Surface Elevation (ft)
 - Velocity (ft/sec)

- Froude Number
- Courant Number
- Lateral Withdrawal (cfs)
- Mannings n
- Width (ft)
- Area (ft)
- Constant Lateral Inflow (cfs)
- Time Varying Lateral Inflow (cfs)
- Hydraulic Depth (Area/Depth, ft)
- Depth (ft)
- Time Step (sec)
- **Error File:** This file will have the same name as the master input file but with the extension *.ERR. It contains diagnostic information. For example, it will write out information to identify problem locations as the number of iterations approaches the maximum.
- **Linkage File:** This file will also have the same name as the master input file but with the extension *.HYD. This is the hydrodynamic linkage file. It contains all of the morphometric and transport information needed by the quality model.

4.4.4. Model Calibration

Calibration usually refers to the identification of site-specific values for coefficients as obtained by varying model coefficients until good agreement is obtained between observed and predicted data. The

objective of the calibration is to reproduce observed data at an acceptable level of accuracy.

The first step of the calibration process is usually just to test the model setup to insure that the model will run and produce meaningful results. Since the users have complete control over their model system, they should try to produce simulations with known results. The simulations could be under steady flow conditions, for example. If errors are identified, then modification of the grid, time step, or hydraulic control parameters may be required (see Section 4.4.5: Trouble Shooting).

In the calibration process, comparisons are usually made between observed and predicted stage, rather than flow. Flow is a derived quantity (for example from stage/discharge relationships). However, comparisons of flow are still useful for making sure that all of the water is accounted for (completing a check of the water balance). Comparisons of velocities (unless they represent averaged values) are of lesser usefulness. Comparison to dye concentrations (by linking the hydrodynamic results to the quality model) is also a very good check on model predictions.

Some of the problems often encountered in calibration are that the model will not reproduce either the timing or shape of a downstream hydrograph or it will work well for one set of conditions and not another. In RIV1H the only coefficients that are typically varied during the course of the calibration are the bottom roughness coefficients (Manning's n). Manning's n may be adjusted within a relatively narrow range, as defined by the literature values for a certain stream type (see Section 4.3.3.2). The impacts of increasing Manning's n are to

- increase travel times, and
- reduce flood flows and elevations.

The user may adjust Manning's n to match both high and low flow periods of an event. In some cases it may be necessary to increase Manning's n during high flows using the stage relationship to compensate for the increased roughness of overbank areas.

The remainder of the calibration exercise is really a testing exercise for the geometry and boundary forcings. If good agreement can not be obtained through adjustment of Manning's n , then the user must become a detective to determine what is causing the problem. It is usually because something was incorrectly specified or left out. For example, errors in the geometric characterization or estimates of bottom slopes may prevent the model from accurately predicting variations in water surface elevations. These errors may only become apparent when the model predictions are compared to field data. The errors may also lie in the calibration data or result from some unique event that occurred during the period the calibration data were collected.

The users should not assume that the hydrodynamic calibration is complete until they have conducted tests with the quality model. For example, errors that are not apparent in comparisons with water surface elevations may become apparent when examining water quality concentrations. Errors or problems with the quality simulation may require the user to return to, and refine, the hydrodynamic model application.

4.4.5. Trouble Shooting

RIV1H is a very robust model capable of simulating a wide variety of dynamic conditions in streams and rivers. However, when running the model the user may encounter start up or stability problems that have to be corrected before meaningful results can be achieved. These problems may be evidenced by the model failing to converge on a solution, producing negative depths or "going dry". That is, the model will not run at all or will "crash" under certain conditions. Problems can also result in numerical oscillations in model predictions. In these situations, the model will run but will produce answers that are not meaningful. The oscillations can be detected by carefully examining the output of RIV1H. In some cases the problems can also be detected when running conservative tracer tests with the quality code (RIV1Q). Problems during model start up can result from incorrect morphometry or poor initial conditions. Phase errors can also occur associated with unsteady flow waves. Streams with riffle sections accentuate these problems.

All one-dimensional hydrodynamic models have difficulty simulating systems with steep slopes, such as mountain streams. If the flow becomes supercritical, then the model may crash or not be able to converge on a solution. One measure of critical flows is the Froude number (F_r),

$$F_r = \frac{\left(\frac{Q}{A}\right)}{\sqrt{g \frac{A}{B}}}$$

Equation 4-6

where Q is the flow, A the cross-sectional area, B the top width and g gravitational acceleration. If $F_r > 1$, then the flow is supercritical. This condition will result in instabilities in RIV1Q even if RIV1H runs. The user may elect to either “smooth” the slope to remove these conditions or increase the bottom roughness coefficient to increase drag in the area where supercritical flows are encountered.

If inaccurate initial depths are selected for the initial flows, the model will have trouble getting started. This may be evidenced by the model becoming unstable as evidenced by it failing to converge, computing negative depths or “going dry.” If the users encounter these errors when they first start the model they must first have to determine where and why the problem occurs. They may want to reduce the print interval at the beginning of the simulation to write out results very frequently so they can be examined to determine the cause of the start up problem. Poor estimates of initial conditions can be particularly problematic where it is necessary to specify flows at the downstream boundary (for example for specifying the controlled outflows from a structure). This situation should be avoided if possible.

Estimates of initial depths may be available from previous modeling or field studies, or steady flow hydraulic models. If good initial estimates of depths are not available, it is best to run the model for a steady-state flow condition using deeper than expected conditions. If lateral inflows and outflows are significant, it may be necessary to include them in these simulations as well. If head is specified downstream, then the head may be likewise initially greater than the expected condition and then correspondingly gradually decreased toward the expected condition. With a constant inflow rate and using a rating curve downstream, or head, the water surface in the segment will eventually drop to a steady-state water surface profile corresponding to that flow, channel geometry, and bed roughness. If problems are still encountered starting the model, the use of small time-steps, at least initially, has helped. After a steady-state

flow and water surface profile have been achieved, it is best to use these results to start subsequent simulations.

Problems may also be encountered when using tabulated cross-sections where either there are multiple x-coordinates with the same y coordinate, which may result in a division by zero in the computation of areas, or where there are large changes in widths over short vertical distances. For example, if the predicted water surface elevation is just at the point where a large change in width (and subsequently area) occurs, then the solution may oscillate just above and just below that point and fail to converge. For such a case it may be necessary to smooth this transition. If a division by zero error is encountered in the area computation, the user may need to increment the y-value slightly. The model error output provides the location of an instability to aid the user in identifying where the problem occurred. However, the problem may not actually be at the locations where the instability occurred, but may, for example, be just upstream.

Phase errors, which may accompany unsteady flow waves, can result in negative depths (usually in or near shallow riffle sections). If this happens, a fatal execution error occurs, and the program is stopped. Several things can be done to eliminate this problem. First, make sure that the cross-sectional area is adequately described, especially at low stage. Next, check the value of THETA (see Section 4.3.4.1: Hydraulic Parameters); a higher value (e.g. 0.75) may help. If problems are still encountered, it may be necessary to change the time-step such that the surface wave Courant number is closer to 1.0. As values of this number decrease below or increase above 1.0, phase errors become worse (Lyn and Goodwin 1987, Liggett and Cunge 1975). The surface Courant number is defined as

$$C_r = \frac{\Delta x}{U_s \Delta t}$$

Equation 4-7

where U_s is the speed of the surface wave ($= \sqrt{gH}$ where H is the depth and g gravitational acceleration), Δt is the time-step size and Δx is the spatial step size. The Courant number also limits the time step that can be used in the quality model. So, the user should also adjust the time step so that a number less than one is achieved throughout the simulation prior to linking the hydrodynamic and quality model. The same result can be

achieved by adjustment of the spatial steps. The Courant number is computed by the model and provided in model output.

Large variations in spatial steps, bottom slopes, roughness coefficients (Manning's n), or cross-sectional characteristics between nodes may also cause the hydrodynamic and/or the quality model to become unstable or produce phase errors (such as overshooting or undershooting the correct values). Abrupt changes in the flood wave itself can also cause problems. If adjusting the time or spatial step does not solve the problem, the user should smooth these transitions. Ramping of the inflow hydrograph to yield a gentler, longer wave will usually reduce phase errors since the unsteady flow waves are more spread out. As an example, hydropower turbines can come up to full power in about 5 min; peaking hydropower releases can result in highly unsteady flow waves in the receiving stream. It may be necessary to spread out the generation start-up over 15 to 30 min. Judicious smoothing of the inflow hydrograph can be accomplished without jeopardizing study objectives. Judicious smoothing of the changes in the characteristics (slope, roughness, areas, etc.) between cross-sections may also be required.

4.4.6. Linkage with Water Quality

The linkage of the hydrodynamic model with the quality model is relatively transparent to the users. They need only to indicate at runtime that a hydrodynamic linkage file should be created. The hydrodynamic linkage file contains all the information the quality model needs to define the model grid. For each hydrodynamic time step, the file contains the time step, and then for each cross-section or node, the flows, time-varying lateral inflows, water surface elevations, areas, and widths. The period of the quality simulation needs to lie within the period for the hydrodynamic simulation, but they need not be identical. The model will begin the simulation at the latest of the two specified start times (one for the hydrodynamic and one for the water quality model) and end at the earliest of the two specified end times. The quality simulations can then be made within any window of the period of the hydrodynamic simulation.

The quality model will generally assume that the hydrodynamic linkage file it will use will have the name of the hydrodynamic input file specified in the project file, but with the extension *.HYD. However, the user will be

prompted at runtime to determine if they want to use some other linkage file.

5. Model Application: Water Quality

5.1. Overview of Solution of Mass Balance Equations

The quality component of CE-QUAL-RIV1 (RIV1Q) was designed to simulate quality variations in river systems under highly unsteady flow conditions. Since the speed of flow waves is often quite high, water quality concentrations can be dominated by advective transport but affected by biogeochemical interactions and diffusion. Therefore, the water quality model is dynamic and has the following attributes. The model:

- Accounts for time-varying flow, elevation, and water quality constituent changes resulting from highly unsteady flows.
- Includes the direct explicit interaction of flow and elevation on the constituent distributions.
- Is applicable to a river channel of arbitrary cross section and specified bottom slope.
- Allows for a number of water quality constituents and the proper mathematical specification of their mathematical interrelationship.
- Accounts for the effects of lateral inputs of water and associated pollutant concentrations.
- Allows simulations of multiple hydraulic control structures.

The basic equation solved by RIV1H is the based upon the **conservation of mass**: a statement that the rate of change of mass stored in a system must equal the quantities of mass entering a system (i.e. due to transport, loads or internal reactions) minus the mass leaving the system due to transport, transformation or degradation. For a one-dimensional system, after some manipulation, the conservation equation may be written as:

$$\frac{\partial \alpha}{\partial t} + u \frac{\partial \alpha}{\partial x} = D \frac{\partial^2 \alpha}{\partial x^2} + \frac{q}{A} (\gamma - \alpha) - K_s \alpha + \text{SINKS}$$

Equation 5-1

where:

α	= constituent (i.e. dissolved oxygen, temperature, etc.)
u	= velocity
x	= longitudinal distance
q	= lateral inflow rate
D	= dispersion coefficient
γ	= concentration of the runoff input to the channel by distributed flow q
K_s	= biochemical uptake or decay rates (+) and growth rates (-)
SINKS	= biochemical sources (+) and sinks (-)

The first term on the left hand side of the above equation represents the time rate of change of constituent concentration. The second term represents advection of the constituent. On the right hand side, the terms represent diffusion, lateral loadings (or withdrawals), reactions and sources/sinks. The reactions are those effecting the particular constituent, such as decay or decomposition. The source and sink terms may represent sources from other constituents (e.g. nitrification is a reaction term for ammonia and a source term for nitrate) or external sources (e.g. surface heat exchange is a source term for temperature). When solved, the mass balance equation permits the calculation of downstream histories of constituent concentrations.

5.2. Schematic of Water Quality Model

The water quality component of CE-QUAL-RIV1 (RIV1Q) was designed to combine hydraulic information received from RIV1H with mathematical specifications of the kinetics of, and interrelationships between, water quality constituents in order to simulate variations in water quality under highly unsteady flow conditions.

5.2.1. Solution Scheme

As with the hydrodynamic model, since there is no analytical solution to the governing equations except for very simplistic conditions, they must be solved numerically. Since any number of species could conceivably be

solved for, the numerical solution must be as quick as possible. This suggests the use of explicit time-marching procedures. However, simple explicit (and also simple implicit methods) time marching for the advection problem is a very severe test for which, unfortunately, the simple methods fail to provide the desired accuracy. Pure advection is the single most difficult test for a numerical method since the initial concentration distribution imposed on the problem must be numerically advected or transported without loss of mass, shape, and peak value, or distortion of the statistics of the distribution including mean, variance, skew, and kurtosis.

A powerful and accurate explicit method based upon a compact, but fourth-order accurate, numerical expression is used to solve Equation 5-1 for advection. The compact, fourth-order accurate scheme presented by Holly and Preissman (1978) is used for all advective mass transport calculations. An implicit fractional step method is subsequently used for the dispersion term.

5.2.2. Water Quality Kinetics

Equation 5-1 applies to all water quality constituents. What defines a particular constituent are the concentrations assigned to the boundaries and lateral inflows and the number and kind of reactions and sources/sinks. The transport variables (velocities, flows, areas, etc.) are common to all water quality constituents.

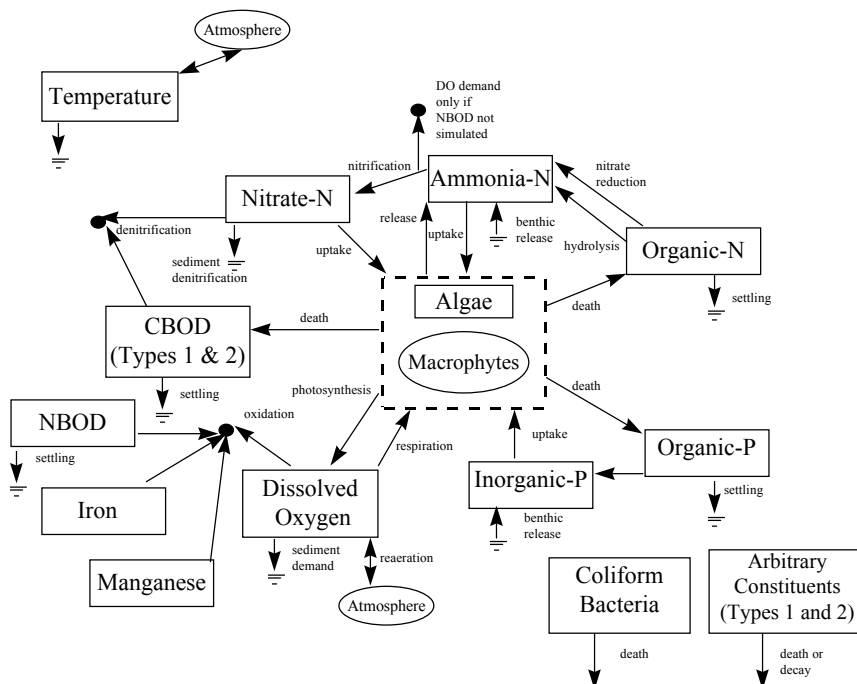


Figure 5-1

RIV1Q has the capability of simulating variations in up to the 16 state variables, and the interrelationships between these are illustrated in Figure 5-1. RIV1Q can also exclude any of these state variables from simulations.

The rate of variation for each state variable, and the interactions between them, are determined using specified kinetic rate and stoichiometric coefficients. The kinetic rate coefficients are input by the user. Some of the coefficients and kinetic rates are assumed to be constant over the system (global values), while others may be varied between branches or between individual cross sections.

A brief discussion of the kinetic transformations for each state variable is provided below. detailed discussion of the interrelationships is provided in Section 7.3.

5.2.2.1. TEMPERATURE AND SOLAR RADIATION

Temperature simulations are based on either a full heat balance or a simple equilibrium temperature approach. Using the full heat balance approach, each term in the heat balance equation is computed, based on algorithms from the QUAL2 model (Brown and Barnwell 1987), including: net short-wave radiation, net long-wave radiation, heat loss due to evaporation, and heat transferred by conduction at the water surface and bottom. The net effect of these individual components of the heat balance is then used by RIV1Q to compute a change in temperature. The computations in the full heat balance depend upon: water temperature; time of the year and day; site latitude, longitude, and elevation; and local meteorological data. The water temperature used in the computations is that predicted during the previous model time step. The time-varying meteorological data are read from external files by RIV1Q. Different meteorological conditions can be assigned to different portions of the model grid, with a limit of five sets of meteorological data. The effect of canopy or bank shading may be simulated by specifying a shading coefficient, and the computed solar radiation is reduced by one minus that fraction.

In the equilibrium temperature approach, the net effects of the individual terms in the heat balance are computed externally to the model and incorporated into an equilibrium temperature and coefficient of heat exchange. The equilibrium temperature is that temperature which will be achieved when the water reaches an equilibrium with the meteorological conditions and the coefficient of heat exchange reflects the rate at which that equilibrium will be achieved. Presently in RIV1Q, the equilibrium temperature and coefficient of heat exchange are constants. That is they are not allowed to vary with time.

Time-varying solar radiation is computed by RIV1Q when the full heat balance option is selected, based upon the time of the day and year; local latitude and longitude; cloud cover, and a specified dust attenuation coefficient. Under the equilibrium temperature approach, solar radiation is not predicted. Dawn, sunset and the daily noon light intensity are specified as constants and then the light during daylight hours estimated using a sine curve. The attenuation of solar radiation through the water column is computed using an extinction coefficient reflecting a base value to which is added the effect of algal self-shading, using an expression extracted from the QUAL2 model.

5.2.2.2. DISSOLVED OXYGEN DYNAMICS

Dissolved oxygen is transferred by reaeration, produced by algae and macrophytes, consumed by the death of algae and macrophytes; consumed by nitrification or nitrogenous biochemical oxygen demand; consumed by sediment oxygen demands; and consumed by CBOD (Types 1 and 2), iron, and manganese oxidation (Figure 5-1). A certain fraction (user specified) of the algal and macrophyte mortality is assumed to contribute to CBOD. The remainder is assumed to be oxidized immediately, producing an oxygen demand. The consumption and production of oxygen by algal and macrophyte productivity and death, as well as by nitrification and oxidation, are related to other state variables through stoichiometric coefficients. The stoichiometric coefficients affecting dissolved oxygen utilization are specified by the user.

Reaeration refers to the transfer of oxygen across the air-water interface. This transfer is affected by the difference in dissolved oxygen concentrations between the air and water as well as by the turbulence in the film of water adjacent to the surface. The turbulence in that thin film may be due to wind shear or shear produced by the water currents and controls the rate of transfer. The rate of wind driven reaeration is computed in a subroutine based on O'Conner's (1983) formulations. The rate of reaeration due to current shear is computed in RIV1Q using either:

- Tsivoglou-Wallace formulation.
- An empirical expression in which the user specifies the coefficients. The default values of the coefficients are those for O'Connor-Dobbins.
- Covar's method.
- A user specified coefficient, which may be varied by node.

Oxygen solubility is computed from Elmore and Hayes (1960) or using APHA's 1985 DO saturation equation, as a user option. At the option of the user, the DO saturation may also be corrected for elevation.

Reaeration may also occur as water passes over or through control structures. Structural reaeration may be simulated using Wilhelm's equation (Wilhelm, S.C. and Smith, D.R. 1981. Reaeration Through Gated-Conduit Outlet Works. Technical Rept. E-81-5. US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi).

Sediment oxygen demand (SOD) is not simulated by RIV1Q. Rather, the effects of SOD on dissolved oxygen are computed from user specified rates, which can be varied between nodes or cross sections. The rates are then adjusted according to the local depth and temperature. The effect of temperature is computed using a temperature coefficient input by the user.

5.2.2.3. BIOCHEMICAL OXYGEN DEMAND

There are three forms of BOD that may be simulated with EPD-RIV1, two forms of carbonaceous BOD and NBOD (Figure 5-1). All of the forms simulated are the **ultimate BODs**. The CBOD represents the amount (as chemically equivalent oxygen) of biodegradable organic matter present, excluding organic nitrogen. The CBOD (ultimate) is simulated using kinetic losses due to aerobic oxidation (temperature corrected), anaerobic oxidation by nitrate reduction (denitrification), and settling. A user specified fraction of the decaying algae and macrophytes are assumed to contribute to CBOD (using a specified fraction), the remainder being oxidized immediately.

The kinetic loss of CBOD due to oxidation is estimated from a user specified rate which is then adjusted according to dissolved oxygen concentrations. The rate of CBOD decay may approach zero as dissolved oxygen approaches zero, as computed using a user specified dissolved oxygen concentration at which CBOD decay is at one-half its maximum rate. Conversely, the rate of denitrification may increase toward its maximum rate as dissolved oxygen and nitrate concentrations approach zero. Therefore, in the absence of oxygen and nitrate there is no CBOD removal. The rates of oxidation CBOD and denitrification are also adjusted according to the effects of temperature using a Q10 formulation.

Nitrogenous biochemical oxygen demand (NBOD) is treated similarly to CBOD. The NBOD (ultimate) is simulated using kinetic losses due to aerobic oxidation (temperature corrected) and settling. The kinetic loss of NBOD due to oxidation is estimated from a user specified rate which is then adjusted according to dissolved oxygen concentrations and temperature. The rate of NBOD decay may approach zero as dissolved

oxygen approaches zero, as computed using a user specified dissolved oxygen concentration at which NBOD decay is at one-half its maximum rate. To avoid “double-dipping”, if NBOD is simulated (not by-passed), then dissolved oxygen concentrations are reduced by NBOD but not by nitrification of ammonia.

5.2.2.4. ALGAE

Algae are modeled as a state variable (subject to transport) in RIV1Q (Figure 5-1). The rate of algal growth is computed from a specified maximum growth rate which is modified by available light. Algal growth is also limited by nitrogen (ammonia and nitrate) and inorganic phosphorus. RIV1Q uses a multiplicative approach for light and nutrient limitations to growth, similar to that in QUAL2 (instead of a minimum). Algal death occurs continuously and is modified according to dissolved oxygen concentrations. The user may specify a dissolved oxygen concentration at which death occurs at one-half of its maximum rate, which is then used to correct the rate of algal death.

5.2.2.5. MACROPHYTES

While the effects of macrophytes are included in RIV1Q, macrophytes are not modeled as a state variable (subject to transport, Figure 5-1). macrophytes were added primarily to include their impacts on dissolved oxygen and nutrient cycling in rivers.

The effects of macrophyte growth on the RIV1Q state variables are computed from the product of a specified macrophyte density and a specified growth rate. The growth rate is modified by the availability of light, which may vary over the course of the day, allowing simulation of diel variations. Unlike algae, the rate of macrophyte growth is not limited by nutrient availability in RIV1Q, since macrophytes can theoretically obtain nutrients from the sediments (which is not modeled) as well as the water column. The rate of macrophyte death is estimated from the product of the a specified macrophyte density and death rate. An option is included to reduce the rate of death, or decay, as dissolved oxygen concentrations approach zero, through a user specified dissolved oxygen half-saturation constant.

5.2.2.6. PHOSPHORUS SPECIES

RIV1Q simulates organic phosphorus and phosphate, or inorganic phosphorus (Figure 5-1). Organic phosphorus is produced by the decay of algae and macrophytes and lost due to decay and settling. The production of organic phosphorus by algal and macrophyte death is computed using a stoichiometric coefficient representing an assumed phosphorus content.

Phosphate is lost due to uptake during algal and macrophyte growth and gained due to sediment release and the decay of organic phosphorus. Sediment releases of phosphorus are computed from user specified rates. The rates are then adjusted according to the local depth and temperature. The effect of temperature is computed using a Q10 formulation, where the temperature coefficient is input by the user.

5.2.2.7. NITROGEN SPECIES

RIV1Q simulates organic nitrogen, ammonia and nitrate-nitrogen (Figure 5-1). Organic nitrogen is produced by the decay of algae and macrophytes and lost due to hydrolysis, nitrate reduction (denitrification) and settling. The production of organic nitrogen by algal and macrophyte death is computed using a stoichiometric coefficient representing an assumed nitrogen content.

Ammonia-nitrogen is lost due to nitrification and uptake by algae and macrophytes. The loss rate due to uptake is based on the fraction of ammonia available as compared to nitrate-nitrogen. The rate of nitrification is dependent upon temperature and dissolved oxygen concentrations. The hydrolysis of organic nitrogen represents a source term for ammonia, as does the death of algae and macrophytes. Sediment releases of ammonia-nitrogen are computed from user specified rates. The rates are then adjusted according to the local depth and temperature. The effect of temperature is computed using a Q10 formulation, where the temperature coefficient is input by the user.

Nitrate-nitrogen is formed by nitrification of ammonia and removed by denitrification in the sediments, denitrification (or anaerobic utilization of CBOD) in the water column, and uptake by algae and macrophytes.

5.2.2.8. IRON AND MANGANESE

As modeled by RIV1Q, iron and manganese have no autochthonous sources. That is, they can enter the system only through boundary conditions (upstream, tributary or lateral inflows). Their oxidation is treated as a simple first-order loss, which is assumed not to occur if dissolved oxygen concentrations fall below a user specified threshold value. The first order rate constants are not temperature corrected. The effect of iron and manganese oxidation on dissolved oxygen is included in the model.

5.2.2.9. COLIFORM BACTERIA

As with iron and manganese, coliform bacteria are assumed by RIV1Q to have no autochthonous sources. That is, they can enter the system only through boundary conditions (upstream, tributary or lateral inflows). Their mortality is treated as a simple first-order loss, which is temperature corrected using a Q10 formulation.

5.2.2.10. ARBITRARY SUBSTANCES

There are two arbitrary constituents included in the model. They may be either conservative or decay according to first order rates specified by the user, which may be temperature corrected. As with coliforms, the arbitrary constituents are assumed to have no autochthonous sources.

5.3. Data Preparation

5.3.1. Linkage with Hydrodynamic Model

A hydrodynamic linkage file is required in order to run RIV1Q. The user must have created a hydrodynamic input file, run the hydrodynamic model, and created a linkage file prior to running the quality program. The quality code gets all of the transport information from this file. The quality file must have the same number of branches and nodes as the hydrodynamic file. At runtime, the default linkage file will be one with the same name as the hydrodynamic input file specified in the project, with the extension *.HYD. However, the users will be prompted to allow them to select an alternative linkage file.

5.3.2. Kinetic Data

Each of the arrows in Figure 5-1 represents a kinetic process that proceeds at a rate which is controlled by the user through their input of kinetic data. The kinetic data include rate constants, which indicate the rate at which the kinetic process proceeds (e.g. nitrification rates, CBOD decay rates, etc.). There are also coefficients for correcting rates due to variations in temperature and dissolved oxygen concentrations. The kinetic data include stoichiometric constants, relating the content of one variable to another, such as the nutrient content of algae. The kinetic data also include options whereby the user may select a particular method for computing a kinetic rate, such as the rate of reaeration.

Some of the rates are global, meaning that they can not be varied over the model domain. Others may be varied by branch and a few can be varied between individual nodes.

There are a relatively large number of kinetic data that may be specified by the user. It is doubtful that all of the available coefficients would be needed for any specific application. The number and type of kinetic data required depend upon the state variables being simulated and the needs of the specific application. The kinetic data that may be specified for each state variable and kinetic process are discussed in detail in Section 7.3.

5.3.3. Initial Conditions

The user must provide initial concentrations for each of the state variables they are simulating at every node in the system. Accurate initial conditions are only meaningful until they are flushed out of the system. Therefore, as the flushing time becomes short, the relative importance of having accurate initial conditions becomes less. For systems with short flushing times with respect to the length of the simulation, the user may often either ignore the model predictions until after the first few flushing times or run the model using their initial boundaries and loadings and use those predictions for their initial conditions. For a system with a long retention time, having accurate initial conditions may be critical.

The user must also first convert available data into the form used in model input. For example, field data or predictions from watershed models may include only total nitrogen or total phosphorus rather than the individual forms simulated by the model. Additional data are required then to

partition the total forms into those used, and these data are site specific. That is the partition should be based upon data from the specific, or very similar, sites.

There are three forms of BOD that may be simulated with EPD-RIV1, two forms of CBOD and NBOD. All of the forms simulated are the **ultimate BODs**. That is, if the user has BOD₅ data, they must first be converted to ultimate concentrations before using them as boundary, lateral inflow, or initial conditions. A ratio of 2.46 for CBOD_u/BOD₅ is typical for highly treated effluent, or 2.85 for CBOD_u/CBOD₅. Thomann and Mueller (1987) summarized the range of CBOD_u/CBOD₅ for municipal wastewater as follows:

Table 5-1. Typical ranges of CBOD_u/CBOD₅ for municipal wastewater (Thomann and Mueller 1987)

Treatment Level	CBOD _u /CBOD ₅	CBOD _u /BOD ₅
Raw Wastewater	1.2	no data
Primary/Secondary	1.6	no data
Activated Sludge	3.2	no data
Advanced Primary	2.84	2.47

However, data strongly suggest that site specific data be obtained for a waste load allocation study to characterize the organic composition and ultimate to 5 day CBOD ratio in both the wastewater and receiving water. Similarly, site specific data are required for other sources of CBOD, such as tributaries and non-point sources.

5.3.4. Model Forcing Data

5.3.4.1. BOUNDARY CONCENTRATION CONDITION.

The boundary conditions required by EPD-RIV1Q are concentrations for each of the state variables simulated (for the external boundaries). The boundary conditions files contain both flow and quality information. Therefore, the boundary condition file used in the quality simulation will typically be the same as that used in the hydrodynamic simulation.

In the boundary condition file the user specifies which state variables will be included. Values should be provided for each of the variables simulated. The user then provides a date (day, month and year) and time

(decimal hours, e.g. 1.0, 24.0) for each series of input concentration. A separate file is prepared for each boundary condition. The user specifies the branch that the file contains the boundary condition for, and selects whether the model will linearly interpolate, or not, between boundary updates.

Boundary conditions are only required for the upstream-most node of the main stem or tributary. If no tributaries are being simulated, then boundary conditions are only required for the most up-stream node. That is, the type of boundary conditions required is determined once the network structure is fixed. For the case where two branches are connected by a control structure (an internal boundary) the predicted concentrations from the last node of the upstream branch become the boundary conditions from the lower branch. The internal boundary conditions are computed by the model and are not specified in the input.

As with the hydrodynamic model, the boundaries drive the simulation and the boundary conditions must be as accurate and as complete as possible. If these data are inaccurate, then the model predictions will be as well. As stated earlier, it is a useless exercise to attempt to calibrate the model to field data when the data used to drive the model are inaccurate.

5.3.4.2. METEOROLOGICAL BOUNDARY CONDITIONS

If temperature is being simulated using a full heat balance, then meteorological boundary condition data are also required. Up to five meteorological data files may be selected, each applying to a different part of the modeled grid. The extent of the grid to which each file applies is specified by indicating the beginning and ending node. As with the lateral inflow files, these node numbers are assigned by the model. So, the user must first run the model for their grid to obtain these values. The model does not check to see if all nodes have an associated meteorological file, this is left up to the user. In each file the user also specifies a:

- Dust attenuation coefficient,
- latitude,
- longitude,
- longitude of the standard meridian, and

- an option to determine whether the model should linearly interpolate values.

The dust attenuation coefficient is used to attenuate the solar radiation flux. It varies with the optical air mass and season of the year and has values of between 0-0.13 (Water Resources Engineers, Inc. 1967). The latitude and longitude are the local values in degrees. The longitude of the standard meridian is the longitude east of the site in increments of 15 degrees, (e.g., 75, 90, 105, etc.).

The user then specifies the time-varying meteorological data, including:

- dry bulb (air) temperature, °F,
- dew point temperatures, °F,
- wind speed (mi/hr),
- cloud cover (decimal fraction, 0.0 to 1.0), and
- barometric pressure (conventional inch of mercury).

The data required to estimate surface heat exchange are often readily available from meteorological stations. However, these stations are often remote from the location of interest. Where local data are not available, site specific data can often be obtained using relatively inexpensive transportable stations.

A difficulty that may be encountered is in the type of temperature data obtained and the height of the wind speed measurements. Data may be available for relative humidity, wet bulb and dry bulb temperatures, or air temperatures and dew point temperatures. It is often necessary to convert these measurements to the form required.

Field measurements of wet and dry bulb temperature are often made using a sling psychrometer (from psychro, meaning cold) or similar device where the wet bulb temperature is indicated by a thermometer with the bulb covered by a wick saturated with water. The dry bulb temperature is

simply the air temperature (T_a). To compute the dew point temperature (T_d , °F), Brown and Barnwell (1987) first compute the saturation vapor pressure (e_{wb} , in Hg) at the wet bulb temperature (T_{wb} , °F) from

$$e_{wb} \text{ (in Hg)} = 0.1001 \exp(0.03 T_{wb}) - 0.0837$$

Equation 5-2

which is then used to estimate the vapor pressure of air (e_a , in Hg) from

$$e_a \text{ (in Hg)} = e_{wb} - 0.000367 P_a (T_a - T_{wb}) \left(1 + \frac{T_{wb} - 32}{1571} \right)$$

Equation 5-3

where T_a is the air (dry bulb) temperature (°F) and P_a the atmospheric pressure (in Hg, eg. 1 atmosphere = 29.92 in Hg). The dew point temperature (T_d , °F) is then computed from

$$T_d = \frac{\ln \left[\frac{e_a + 0.0837}{0.1001} \right]}{0.03}$$

Equation 5-4

where e_a is the water vapor pressure of the air (in Hg).

Relative humidity, another alternative measurement, is the ratio of the mass of water vapor to the mass of water vapor required to produce a saturated mixture at the same temperature in a constant flow of air. The dew point temperature is often used to calculate the relative humidity, thus the relative humidity can be used to estimate the dewpoint temperature. Dew point temperature is usually measured by cooling a metal plate until moisture condenses the dew. The temperature of the plate at which condensation occurs is called the dew point temperature. The relative humidity is the ratio of the vapor pressure at the dew point temperature to the vapor pressure at the air temperature. To illustrate, the respective vapor pressures for the dew point temperature and the air can be evaluated using (Environmental Laboratory 1985)

$$e_a = 2.171 \times 10^8 \exp\left(\frac{-4,157}{T + 239.09}\right)$$

Equation 5-5

where T is the temperature (°C) and e the vapor pressure (mb). Evaluating the vapor pressure at the dewpoint temperature (e_s) and air temperature (e_a), the relative humidity is then $(e_a / e_s) 100$.

Where the atmospheric pressure is not known at a site, it may be estimated from its elevation and air temperature in relation to a reference elevation and pressure. This is accomplished by integrating the ideal gas law over the change in elevation relative to the datum (Plate 1982, cited in Brown and Barnwell 1987)

$$P = P_o \exp\left[-\frac{g}{R(T_a + 460)}(z - z_o)\right]$$

Equation 5-6

where P is the atmospheric pressure at a given elevation (in Hg), g is gravitational acceleration (32.2 ft sec⁻²), R is the gas law constant (1715 ft² sec⁻² °R⁻¹), T_a the air temperature (°F), z the elevation (ft), and z_o and P_o the datum elevation and pressure, respectively. The factor of 460 converts the air temperature in °F to the absolute temperature in °R.

5.3.4.3. LATERAL INFLOWS

The lateral inflows specified to RIV1Q include both point and non-point sources. Data required to specify the lateral inflows are the concentrations associated with the flows used in the hydrodynamic simulation, and the location at which they enter the model network. As with the hydrodynamic model, there are two alternatives provided for entering lateral inflow information: constant and time-varying. The constant lateral inflows are specified along with other node information (initial concentrations). The time-varying data are included as an auxiliary file. The loads (flows times concentrations) from both sources are added together by the model.

If time-varying lateral inflows are specified, the user must create an auxiliary file containing a time series of flows (and concentrations for water quality simulations). The flows and concentrations may be derived from field or monitoring data or estimated by modeling. However, as with boundary conditions, the data should be as frequent and accurate as possible since they directly impact model predictions.

A relatively large number of point and non-point sources may commonly enter the modeled system. The data available from the different sources are often of varying frequencies and quality. However, only a single lateral inflow file may be used in a simulation. The file specifies the nodes or cross-sections at which the lateral inflows enter and then provides a time series of their values (e.g. flows and concentrations, with only the flows being used in the hydrodynamic predictions). Therefore, prior to inputting the data to RIV1Q, the lateral inflows must be processed so that all data are provided at the same frequency. The evaluation of the data and processing of the file is a major function of the DELIBERATOR, and the user is referred to its description for guidance in accomplishing this task. The node at which the inflow is specified to enter is the node number assigned by EPD-RIV1. It is suggested that the model first be run and the node numbers obtained from the output file.

The user may also enter scale and conversion factors for each node and for each quality constituent, which have default values of one. The lateral inflow values multiplied by the scale and conversion factors are used by the model. The user may also elect to have the model linearly interpolate between update intervals or not.

5.3.4.4. WITHDRAWALS

Withdrawals, where water is removed from the system, may be specified in the hydrodynamic simulation. Their impact is automatically included in the quality simulation, using information obtained from the hydrodynamic linkage file. No additional information is required.

5.3.4.5. POWER PLANTS

The impact of power plants can be simulated in RIV1Q by specifying their withdrawal rates, in the withdrawal file, and effluent flows and concentrations in the lateral inflow file. Alternatively the user has the option of specifying their impacts using the optional Power Plant feature that assumes no net change in flows due to the power plant and essentially adds heat as a load. For this option, the user specifies the

nodes that receive the power plant flows and a time series of the flow rates and then either the effluent temperature or increase in temperature above the ambient for the power plant. As with all other time-varying inflows, the user can elect to linearly interpolate between time values or not.

5.3.4.6. CONTROL PARAMETERS

Control parameters specified in the quality simulation include the beginning and end time for the simulation and the frequency at which to write results (which can be varied). All other control information is provided in the hydrodynamic linkage file.

5.3.5. Calibration Data

The application of RIVQ also requires that data be available to calibrate and evaluate the model predictions. While it is possible to apply EPD-RIV1 without the use of calibration or evaluation data, it would not be possible to estimate the uncertainty associated with that application. The data usually consist of time series of constituent concentrations at a series of points along the river which can be compared to model predictions, graphically and statistically. A good source of data to test the transport predictions are from dye studies. Comparison with dye concentrations can be accomplished after linking with RIV1H. The time-of-travel of the dye centroid provides a good check of model hydraulic predictions. The dispersion of the dye cloud provides a good check of, or way to determine, the dispersion rates. Concentrations of other constituents are used to determine and test their kinetic rate coefficients.

Generally, at least two sets of data are needed; one set for model calibration and a second, independent, data set for model evaluation. Where field studies are planned to obtain the calibration data, it is important to remember that the model predictions are only as good as the data used to drive the model. For example, it would be a useless exercise to calibrate the model when the boundary forcings are not well known. Ideally, the availability of adequate data should be assessed prior to beginning the modeling study. If sufficient data are not available, then plans should be made for obtaining them. In many cases, an iterative approach is often useful. That is, the sampling plan can be designed with the model in mind. Initial model simulations may aid in evaluating and

identifying deficiencies in the data, which can be corrected in subsequent studies.

5.4. Simulations

5.4.1. Model Preparation

As with RIV1H, once the data have been gathered, they are used to prepare input data sets for the model. The function of the Deliberator and pre-processor are to aid the user in the preparation of these files. The files of that may be used to control simulation include:

The **main input control file** contains the information period of simulation, frequency at which to print, and kinetic data. All other data are provided in the hydrodynamic linkage file. The remainder of the files are referred to as auxiliary files. Of these, only the boundary condition file is required for a simulation. The meteorological file is required if a full heat balance is used. The **auxiliary files** include:

- Boundary Condition File (Separate files for each boundary condition):
 - ◆ branch to which boundary applies
 - ◆ interpolation option (stair-stepped or linear)
 - ◆ dates (year, month, day, decimal hour), flows (cfs) or depths (ft), and concentrations (mg/l).
- Lateral Inflow File (One file only):
 - ◆ locations (node numbers) receiving lateral inflow
 - ◆ interpolation option (stair-stepped or linear)
 - ◆ dates (year, month, day, decimal hour), flow rates, and concentrations (mg/l).
- Meteorological File (Up to five files):
 - ◆ locations (node numbers) receiving lateral inflow

- ◆ interpolation option (stair-stepped or linear)
- ◆ Latitude, longitude, longitude of standard meridian, and dust attenuation coefficient
- ◆ dates (year, month, day, decimal hour), dry bulb (air) temperature (°F), dew point temperatures (°F), wind speed (mi/hr), cloud cover (decimal fraction, 0.0 to 1.0), and barometric pressure (conventional inch of mercury).
- Power Plant File (Optional)
 - ◆ names of cross-section
 - ◆ interpolation option (stair-stepped or linear)
 - ◆ power plant option (temperature represents effluent temperature or increase in temperature of effluent above ambient.
 - ◆ dates (year, month, day, decimal hour), flow rates (cfs) and temperatures

As with RIV1H, the files to be used in the simulation are specified in the **project file**.

5.4.2. Model Simulations

Once the input files are prepared, and the project file completed, the users should return to the SHELL and select the project. If a hydrodynamic linkage file does not exist, then they must first run RIV1H. otherwise, they can run RIV1Q from either the file menu or by clicking on the run icon for Q (RIV1Q). Before the model executes, the users will have to respond to three questions:

- 1) Do you want to create a report ?
- 2) Do you want to use the linkage file created using the hydrodynamic input file specified in the project file (otherwise the users will be prompted to select the linkage file)?

3) Do you want to write out time-varying data?

If the users say yes to the first question, they can fill out a form which documents the simulation. Additional information describing the input files, control information, and length of simulation will be appended to the information the users provide. The users can then save the file at the end of the simulation.

If the users say no to the second question, they will be prompted to select a linkage file. Otherwise, the model will use the linkage file specified as part of the project.

If the users say yes to the third question, then information will be written to the output file each time that time-varying information is updated from the auxiliary files. This is usually only needed to aid in diagnosing errors.

After these questions have been addressed, the model will execute. During execution, intermediate model results will be displayed (Figure 5-2). The users may scroll through the model nodes or through the display variables. If the users encounter a problem that they need to correct, that may stop the program. Also, the priority of the job may be changed during the simulation. The users may pause (stop) the simulation if they need to do something else or may maximize the priority by putting the model in turbo mode. The fastest run times will occur if they shut off the writing of the intermediate simulation results and turn the model to turbo.

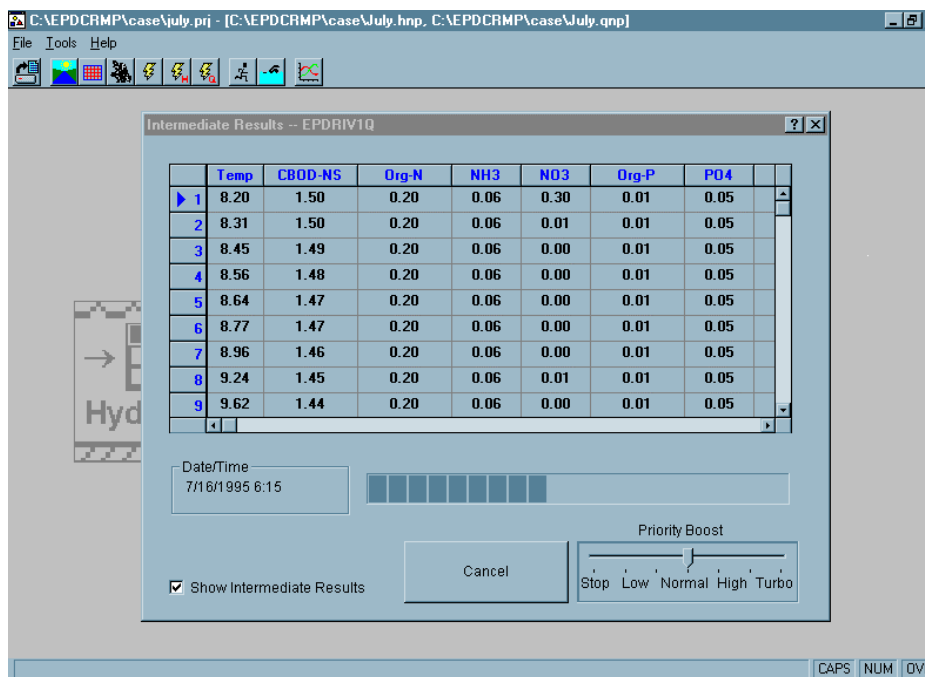


Figure 5-2

Once the simulation is complete, the grid will disappear and they will be back in the shell. If the users created a report, they will be asked to save it at this time. The users may then view the output files or graph the simulation results.

5.4.3. Model Output

The output from the model includes the intermediate screen results and the simulation report. Additional files created that the users can view include:

- Output File:** This file mimics the input. When created, it will have the same name as the master input file but with the extension *.OUT. It contains much of the same information as the report prepared by the pre-processor. In addition, there are diagnostic messages which are written to this file. It is a text file that must be examined by an editor or word-processor (for convenience the users should put their favorite editor on the tool menu in the SHELL).

- **Graphics File:** A graphics file will be created with the same name as the master input file but with the extension *.BMD. The graphics file is used by the post-processor and contains the same result information as is written to the screen during runtime. The output includes variables passed from the hydrodynamic model (e.g. flows and velocities), concentrations for the model state variables, and those intended to aid the user in evaluating the model results (e.g. decay rates, dissolved oxygen deficit, etc.). The following information is written to the file at the frequency specified by the users for each model node:
 - Information from Linkage File:
 - ◆ Distance (miles)
 - ◆ Stage (feet)
 - ◆ Velocity (ft/sec)
 - ◆ Flow (cfs)
 - ◆ Hydraulic Depth (ft)
 - Predicted Concentrations
 - ◆ Temperature (°C)
 - ◆ CBOD (mg/l)
 - ◆ Organic-N (mg/l)
 - ◆ NH3-N (mg/l)
 - ◆ NO3-N (mg/l)
 - ◆ Organic-P (mg/l)
 - ◆ Inorganic P (PO4, mg/l)
 - ◆ Manganese (mg/l)
 - ◆ Iron (mg/l)

- ◆ Dissolved Oxygen (mg/l)
- ◆ Coliforms (counts/100 ml, depending on user input)
- ◆ Algae (biomass, mg/l)
- ◆ CBOD Type 2 (mg./l)
- ◆ Nitrogenous BOD (mg/l)
- ◆ Arbitrary Constituent 1 (mg/l)
- ◆ Arbitrary Constituent 2 (mg/l)
- Computed Variables
 - ◆ Dissolved Oxygen Deficit: difference between predicted and saturation concentrations (mg/l)
 - ◆ Dissolved Oxygen Maximum: maximum concentration occurring during period between print intervals (mg/l)
 - ◆ Dissolved Oxygen Minimum: minimum concentration occurring during period between print intervals (mg/l)
 - ◆ Total P: sum of all phosphorus forms (mg/l)
 - ◆ Total N: sum of all nitrogen forms (mg/l)
 - ◆ Total CBOD: sum of CBOD types 1 and 2 (mg/l)
 - ◆ Dispersion rate (ft²/day)
 - ◆ Extinction Coefficient (1/ft)
 - ◆ Phytoplankton N Limit (0 to 1)
 - ◆ Phytoplankton P Limit (0 to 1)
 - ◆ Solar Radiation (W/m²)
 - ◆ Phytoplankton Light Limit (0 to 1)

- ◆ Phytoplankton Growth Rate (1/day)
- ◆ Macrophyte Growth Rate (1/day)
- ◆ Phytoplankton Death Rate (1/day)
- ◆ Macrophyte Death Rate (1/day)
- ◆ CBOD Type 1 Decay Rate (1/day)
- ◆ CBOD Type 2 Decay Rate (1/day)
- ◆ Stream Reaeration Rate. (1/day)
- ◆ Wind Reaeration Rate (1/day)
- ◆ Phytoplankton Concentration as Chlorophyll-a ($\mu\text{g/l}$)

5.4.4. Model Calibration

Calibration usually refers to the identification of site-specific values for coefficients as obtained by varying model coefficients until good agreement is obtained between observed and predicted data. The objective of the calibration is to reproduce observed data at an acceptable level of accuracy.

The first step of the calibration process is usually just to test the model setup to insure that the model will run and produce meaningful results. Since the users have complete control over their model system, they should first try to produce simulations with known results. For example, the first simulation may be made using constant boundary concentrations. If the predicted concentrations do not go to the boundary concentration (if lateral inflows are not included), then a problem exists that must be corrected before proceeding. Another good test is to simulate a slug release of a conservative tracer. If there are phase errors introduced by the flows or grid, the users will see overshoots or undershoots of the concentrations, particularly at the leading or trailing edges of the slug. Similarly, the users should perform other diagnostic tests to determine if the model is running correctly before proceeding, just as they would any other analytic instrument. If errors are identified, then modification of the grid, time step, or hydraulic control parameters may be required (see Section 5.4.5 Trouble Shooting).

In the second step of the calibration process, comparisons are made between observed and predicted concentrations. The users would then determine which coefficients have an impact on the model predictions. The coefficients are then adjusted, within an acceptable range, in order to obtain the best match between the observed and predicted data. After obtaining good agreement, it is often stated that the users would then apply the model to a second, independent set of data, to test the “validity” or “confirm” the model. As indicated by Cole and Buchak (1995), this distinction is artificial. In reality, if the users do not reproduce observed data for the second, or verification, application, they would reexamine the coefficients, model assumptions and setup in order to obtain the best results for both sets of data. That is, they would reexamine and refine their concept of the system and how it behaves in order to obtain one that more closely agrees with the prototype. This is particularly important since the goal of the modeling effort will be to estimate changes that may occur as the result of some action and to determine which actions are most feasible.

Ideally, the user would use as many sets of data as possible in the calibration phase, encompassing a wide variety of conditions. The ability of the model to reproduce observed conditions under a wide variety of conditions tests the robustness of the model, and makes the application more defensible.

Calibration usually proceeds by first calibrating to those variables which are independent of each other. That is, starting with as simple a system as possible and then becoming progressively complex as needed. Comparison to measured dye concentrations is a very good check for model transport predictions. If coliforms are simulated, the predicted concentrations are independent of all other constituents, with the exception of temperature, so that they should receive attention during the initial phases of the calibration. Similarly, iron and manganese are assumed not to have any autochthonous sources and can be addressed early. Similarly, BOD may be relatively independent for systems without large autochthonous sources. Temperature is also addressed during the initial phases of the calibration.

During the calibration phase, the user should compare predicted and observed data using as many tools as possible, statistical and graphical. A variety of methods for comparison are provided by the Post-Processor

for EPD-RIV1. The users should also examine results to determine if they correspond to their and others' concept of how the system operates.

During the calibration, the users should also attempt to identify which model parameters have greatest impact on model predictions. If the model is sensitive to a particular parameter, the users should attempt to gather data to further identify and constrain the range over which that parameter can be varied. The users should also attempt to apply the model using as few parameters as possible for their particular application, since an increase in the use of uncertain parameters leads to an increase in model uncertainty, particularly when it must be applied to conditions outside of the range of the calibration data.

It may also be possible in some applications that a reasonable fit to observed data can not be obtained by varying model parameters over a reasonable range. This usually indicates that there is something incorrect about the application, or some critical process is impacting the system which is either not included in the model algorithms or in the forcing data supplied to the model. For example, if the system is not one-dimensional, lateral variations may occur which the model can not capture. There may also be missing or incomplete data, and the model application may aid in identifying these data deficiencies. Where possible, an ideal approach to obtaining both the optimal set of field data and model setup, is to iteratively conduct modeling and field data collection studies.

5.4.5. Trouble Shooting

RIV1Q, like RIV1H, is a robust model designed to simulate water quality under highly dynamic flow conditions. It can handle a wide variety of conditions. However, there may be cases where the model either becomes unstable and "crashes" or produces unreasonable answers. If the model "crashes", or becomes numerically unstable, then an error will usually occur that will cause the model to stop executing. These types of errors are easily detected, although not always easily corrected. There are also situations where the model will run, but will produce answers that are not meaningful. These types of problems are usually detected only by careful examination of model results and through running diagnostic tests with known solutions, such as conservative tracer tests. Therefore testing of this type is critical to any application.

Many of the conditions wherein the quality model will become unstable are due to the conditions passed from the hydrodynamic model. That is, there

are conditions where the hydrodynamic model will run and produce reasonable answers, but the quality model will not run using the results from the hydrodynamic model. The user should not assume that the hydrodynamic simulations are completed prior to running the quality model.

Two conditions will commonly cause RIV1Q to become unstable: exceeding the Courant number and flow reversals. Although the RIV1H numerical solution scheme is not limited by the Courant number, the scheme used in RIV1Q is. Therefore, there may be cases where the hydrodynamic model will run, but the quality model will not. The surface Courant number is defined as

$$C_r = \frac{\Delta x}{U_s \Delta t}$$

Equation 5-7

where U_s is the speed of the surface wave ($= \sqrt{gH}$ where H is the depth and g gravitational acceleration), Δt is the time-step size and Δx is the spatial step size. If the Courant number exceeds one, then the quality model will become unstable. The Courant number is a computed variable which is included in the graphics output file for the hydrodynamic model. If stability problems are encountered in RIV1Q, then the user should examine the hydrodynamic results to ensure that the Courant number does not exceed one.

The solution scheme presently used in EPD-RIV1Q will not accommodate flow reversals (negative flows). Flow reversals may typically occur near control structures or in tributary arms. Flow reversals may occur intermittently, and they may not cause the model to crash but to produce unreasonable answers. Future versions of EPD-RIV1Q will accommodate flow reversals. However, for the present version, the user should carefully examine the hydrodynamic model output to insure that flow reversals do not occur.

Phase errors can result in overshooting or undershooting concentrations. Phase errors can occur when the Courant number becomes small, producing, for example, negative concentrations. If the negative

concentrations were considered, mass would be conserved. However, there is a “negative hedge” in RIV1Q which sets concentrations to zero if they become negative. These types of phase errors may often be corrected by increasing the Courant number, usually by increasing the model time step. This will, of course, require that the hydrodynamic model be rerun, since the hydrodynamic time step controls the quality simulation. Large variations in spatial steps, bottom slopes, or cross-sectional characteristics between nodes may also cause the quality model to become unstable or produce phase errors. Abrupt changes in the flood wave itself can also cause problems. If adjusting the time or spatial step does not solve the problem, the user should smooth these transitions. For example, ramping of the inflow hydrograph to yield a gentler, longer wave will usually reduce phase errors since the unsteady flow waves are more spread out. Judicious smoothing of the changes in the characteristics (slope, roughness, areas, etc.) between cross-sections may also be required.

Errors may also be introduced near boundary conditions. For example, an incorrect or poor lower boundary condition may produce phase oscillations upstream in the quality predictions. These boundary condition errors may often only be detected with the quality simulation, since hydraulic variables, such as elevations, are less sensitive to the problem.

The model may be numerically stable and accurate, but the user may not be able to obtain reasonable comparisons between predicted and observed data. Some of the kinds of errors that commonly occur include:

- **Water Budget:** Errors in the water budget may be due to missing storm event data, incomplete inflow or outflow data, or missing tributary or seepage inflows. Errors in the water budget can be detected by integrating the measured outflows over time and comparing them to inflows and storage.
- **Bathymetry:** Errors in bathymetry may be caused by leaving out critical cross-sections, resulting in incorrect travel times or timing of the pollutograph. This may be particularly problematic in systems with alternating pond and riffle areas. The user should confirm the bathymetric description in the model by visually inspecting the system. A visual inspection of the system should be part of any modeling study.

- **Inflow temperatures and/or constituent concentrations:** Since the inflows (at boundaries or lateral inflows) are a major driving force, their incorrect specification may preclude the model from accurately predicting observed conditions. The model can only be as good as the data used to drive it.
- **Meteorological Data:** Meteorological data are often taken at stations remote to the study area. Therefore, rainfall coverage used in the generation of loads to the model may be inaccurate. In addition, cloud cover, wind speeds, and other meteorological variables measured at a remote site may not accurately reflect conditions at the site. Frontal movements may also vary between the sites for the model application and data measurement. The user may want to obtain data from several sites for comparison, and use data collected at the site wherever possible. Local variations due to shading or local fog formation may also impact model results.
- **Sediment data:** Errors in measurements of sediment oxygen demand and nutrient releases may impact model results, particularly in slow moving rivers and streams. Also, in alluvial systems, the cross-sectional geometry may change with time.

There are a number of other factors which may result in the model not being able to accurately reproduce observed results. Detecting these usually requires a good understanding of both the model and modeled system.

An understanding of the processes modeled as well as a knowledge of the system being simulated is an absolute must if the modeling effort is to succeed (Cерco and Buchak 1985).

An additional possibility for model errors is “pilot errors” or errors in the model itself. Pilot errors are those due to inaccurate or mistaken input. These can best be detected by careful examination of the model output files and optional report files generated by the pre- and post-processors to ensure that all data were entered correctly. Secondly, while no model developers would like to admit that there is a possibility of errors in their model codes, that possibility always exists. Considerable effort has been

made to test EPD-RIV1 and a criterion for the selection of CE-QUAL-RIV1 as a basis for the model was its history of development and application. However, errors can occur with this or any other complex code or project. As a result, the users should never blindly accept model results that are contrary to their own perceptions or intuition about the modeled system. That is not to say that the model may not be correct. However, the careful user should critically examine such situations to insure that is the case.

6. Hydrodynamics

6.1. The Governing Equations

The hydrodynamic equations solved by EPD-RIV1 are based upon the conservation of both mass and momentum. Mass and momentum, like all conservative properties (as with constituent mass), can not be created or destroyed by ordinary processes. As a result, we can quantify changes that may result in the accumulation (change with respect to time) of these properties in some volume of space, a control volume, by accounting for the processes by which those properties are added or removed from the control volume.

The conservation of water mass equation states that the time rate of change of water mass (accumulation) in a control volume equals the net efflux (i.e. inflows and outflows) through the surface of that control volume. For a control volume of cross-sectional area A and length Δx , the mass is equal to the product of the volume and the water density ($\rho A \Delta x$), and the net efflux is due to the inflow flow rate ($Q=UA$), the outflow, and the change in flows and volume. By a Taylor series expansion, therefore

$$\frac{\partial(\rho A \Delta x)}{\partial t} = \rho \left[\left(U - \frac{\partial U}{\partial x} \frac{\Delta x}{2} \right) \left(A - \frac{\partial A}{\partial x} \frac{\Delta x}{2} \right) - \left(U + \frac{\partial U}{\partial x} \frac{\Delta x}{2} \right) \left(A + \frac{\partial A}{\partial x} \frac{\Delta x}{2} \right) \right]$$

Equation 6-1

where

A = cross-sectional area
 Δx = length of control volume
 ρ = density of water

U = velocity
 x = distance
 t = time

For an incompressible fluid such as water, $\rho = \text{constant}$; multiplying out and dividing by $\rho \Delta x$ gives for small Δx

$$\frac{\partial A}{\partial t} + \frac{\partial(UA)}{\partial x} = 0 \text{ or } \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

Equation 6-2

where Q is the volumetric flow rate.

Momentum, the product of mass and velocity, is also a conservative property. The rate of change in momentum is due to the net force acting upon it. Thus, the momentum equation states that the net force acting on the control volume equals the time rate of change of momentum in the control volume plus the net rate of efflux of momentum through the control volume. Therefore

$$\begin{aligned} \frac{\partial(UA\Delta x)\rho}{\partial t} &= \rho \frac{\partial(Q\Delta x)}{\partial t} \\ &= \rho \left[\left(U(UA) + \frac{\partial}{\partial x} [U(UA)] \frac{\Delta x}{2} \right) - \left(U(UA) - \frac{\partial}{\partial x} \left\{ U(UA) \frac{\Delta x}{2} \right\} \right) \right] \\ &= \bar{F} \end{aligned}$$

Equation 6-3

where the force vector \bar{F} includes the effects gravity, shear, and pressure forces ($\bar{F} = \bar{f}_g + \bar{f}_\tau + \bar{f}_p$)

6.1.1. Gravity Force, \bar{f}_g

The total gravity force is nothing more than the component of the weight of water in the control volume, equal to its density, multiplied by the volume and gravitational acceleration ($\rho g A \Delta x$) directed in the x-direction or $\rho g A \Delta x \sin \theta$. Therefore

$$f_g = \rho g A \Delta x S_o$$

Equation 6-4

where $S_o = \sin \theta \approx \theta$, the bottom slope of the channel.

6.1.2. Shear Force, f_τ

The channel sides and bottoms deplete momentum by the action of bottom friction or shear. This depletion is made mathematically analogous to the gravity slope term by setting

$$f_\tau = \rho g A \Delta x S_f$$

Equation 6-5

where S_f is the friction slope, evaluated using the Manning equation, so that

$$S_f = \frac{U^2 n^2}{(1.486 R^{2/3})^2}$$

Equation 6-6

where

n = Manning's friction factor
 R = hydraulic radius which is approximately equal to A/B , where B is the top width

Therefore,

$$f_{\tau} = \rho g A \Delta x \frac{U^2 n^2}{(1.486 R^{2/3})^2}$$

Equation 6-7

$$f_{\tau} = \rho g A \Delta x \frac{n^2 |Q| Q}{2.2 A^2 R^{4/3}}$$

Equation 6-8

where the absolute value has been retained to ensure that no matter which way the wave propagates, shear always dissipates momentum.

6.1.3. Pressure Force, f_p

The total pressure force on the face of the control volume is the integral of the irregular trace of the control volume, i.e.

$$f_p = \int_0^h \rho g (h - z) \xi(z) dz$$

Equation 6-9

where $\xi(z)$ is the channel width at height z above the bottom. A Taylor series expansion gives the net pressure in the downstream direction

$$\begin{aligned} f_p &= - \frac{\partial}{\partial x} \int_0^h \rho g (h - z) \xi(z) dz \Delta x \\ &= - \rho g \int_0^h \frac{\partial}{\partial x} [(h - z) \xi(z)] dz \Delta x \end{aligned}$$

Equation 6-10

and by chain rule differentiation

$$f_p = - \rho g \left[\frac{\partial h}{\partial x} \int_0^h \xi(z) dz + \int_0^h (h - z) \frac{\partial \xi(z)}{\partial x} dz \right] \Delta x$$

Equation 6-11

The first term represents the pressure force at that particular cross section. The second term represents the net pressure force caused by rapid area changes over the length Δx . If the channels are considered prismatic and regular, then the last term has little significance. Therefore

$$f_p = - \rho g A \frac{\partial h}{\partial x} \Delta x$$

Equation 6-12

The final equation for momentum is then

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} (QU) + gA \frac{\partial h}{\partial x} = gA(S_o - S_f)$$

Equation 6-13

6.1.4. Modifications to momentum and continuity

6.1.4.1. LATERAL AND TRIBUTARY INFLOW.

Runoff from lands adjacent to the channel or tributary inflow can cause increased levels of total mass and momentum in the river. If q is the flow per unit channel length entering the river with velocity U_q , then Equation 6-2 and Equation 6-13 become, respectively,

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$$

Equation 6-14

and

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(UQ) + gA \frac{\partial h}{\partial x} = gA(S_o - S_f) + qU_q$$

Equation 6-15

However, the EPD-RIV1 code does not include the last term in Equation 6-15 because it is relatively insignificant compared with other terms of the momentum equation.

6.1.4.2.CHANNEL CONSTRICTIONS.

Often very intense channel constrictions, due to bridges for example, occur over channel lengths that are far too small to economically resolve in the model. The subgrid scale effect of such constrictions is a momentum loss and backwater effect. This effect is accounted for in the right side of the momentum equation by subtracting the force term, $\rho g \Delta h_E$ where h_E is a head loss and K_E is a coefficient to be selected and optimized.

$$h_E = \frac{K_E}{2g} \left(\frac{Q}{A} \right)^2$$

Equation 6-16

The default value is zero for no constriction loss. A value for K_E as high as 0.5 may be appropriate for an abrupt constriction.

6.1.4.3.MOMENTUM CORRECTION FACTOR.

When the velocity across the channel is substantially non-uniform through the model reach, it may be necessary to use a momentum correction factor β in the momentum equation. The momentum correction factor β multiplies the second term on the left side of Equation 6-15; this correction permits the use of the average velocity, U , in the solution whereas the velocity distribution at each cross section may be quite different from U . For example, for laminar flow in a straight round tube, β is 4/3. It equals 1.0 for uniform flow and cannot be less than 1.0. For RIV1H, a constant value is used throughout the modeled reach. The default value of 1.0 is recommended for rivers and streams.

6.1.4.4. TRIBUTARY NETWORKS.

The momentum and continuity equations above must be applied to each and every tributary entering the main stem. At each junction, the water surfaces in each branch must be equal.

6.1.5. Initial and Boundary Conditions

The solution of the momentum and continuity equations requires that the initial conditions be known, or the conditions at time zero ($t = t_0$) at all locations (nodes) in the modeled grid. For continuity, the only initial conditions to be specified at time $t = t_0$ for all the nodes i for $i = 1$ to N are

$$h(t = t_0, x) = h_i(x)$$

Equation 6-17

where h is the depth, since there is a direct correspondence between the depth and areas (A). For the momentum equation, initial flows are specified

$$Q(t = t_0, x) = Q_i(x)$$

Equation 6-18

For the upstream boundary at $x = 0$ and the downstream boundary at $x = L$, the following sets of boundary conditions may be used for the combined set of continuity and momentum equations. Please note that two first-order equations require only a total of two boundary conditions. Therefore, only one set may be used for each simulation.

$$h(t, x = 0) = h_u(t) \text{ and } h(t, x = L) = h_d(t)$$

Equation 6-19

$$Q(t, x = 0) = Q_u(t) \text{ and } Q(t, x = L) = Q_d(t)$$

Equation 6-20

$$h(t, x = 0) = h_u(t) \text{ and } Q(t, x = L) = Q_d(t)$$

Equation 6-21

$$Q(t, x = 0) = Q_u(t) \text{ and } h(t, x = L) = h_d(t)$$

Equation 6-22

$$h(t, x = 0) = h_u(t) \text{ and } f_1(Q, h) = f_{1d}(t)$$

Equation 6-23

$$Q(t, x = 0) = Q_u(t) \text{ and } f_2(Q, h) = f_{2d}(t)$$

Equation 6-24

where f_1 and f_2 are rating curves relating h and Q for the downstream (d) boundary conditions.

It should be noted that the upstream boundary condition for a tributary can be selected by specifying either the elevation or the flow. At the downstream tributary boundary, i.e. the confluence with the main stem, only the elevation is allowed as a "boundary" condition to ensure that continuity is preserved at the junction.

6.2. Equation Summary

The following equations govern the unsteady, 1-D (longitudinal) hydrodynamics and transport:

Continuity

$$\frac{\partial(A + A_o)}{\partial t} + \frac{\partial Q}{\partial x} = q$$

Equation 6-25

Momentum

$$\frac{\partial Q}{\partial t} + \frac{\partial(UQ)}{\partial x} + gA \frac{\partial h}{\partial x} = gA \left(S_o - S_f - \frac{h_E}{\Delta x} \right) + qU_q$$

Equation 6-26

Equations Equation 6-25 and Equation 6-26 are commonly referred to as the St. Venant equations.

6.3. Numerical Solution for Flow and Elevation

6.3.1. Rationale

As noted, flood and peaking hydropower waves and associated transport are marked by rapidly varying flows, elevations, and concentrations. As derived, the continuity and momentum equations, from which elevations and flows are calculated, are hyperbolic. The transport equation is dominated by advection; thus it has hyperbolic features. All of these equations, then, are very difficult to solve numerically because the smoothing, stabilizing effects of dispersion are eliminated or reduced. Inspection of the governing equations reveals that they are coupled, unsteady, and nonlinear, but because the contaminant concentrations do not affect the flow field, it is possible to uncouple the solution of the continuity and momentum equations from the solution of the species transport equation. Once solved, the complete time histories of flow and elevation can be stored and used as input information for the transport

calculations. Because the governing equations are hyperbolic, the solution procedure for the flows and elevations is quite different from the transport solution; therefore, this part presents the solution procedure for the continuity and momentum equations.

6.3.2. Numerical Approximations

Three numerical procedures are useful for solving hyperbolic equations: the finite element method, the method of characteristics, and implicit, finite difference methods. The method of characteristics is quite accurate but can be difficult to program by anyone but a specialist. Reviews of this method are found in Liggett and Cunge (1975) and Abbott (1979). Implicit, finite difference methods are simpler to program because they are much more direct numerical techniques to approximate partial derivatives. These methods also possess favorable stability behavior even in applications with variable space and time-steps. Explicit finite difference methods are generally unstable and are not considered.

There are many implicit procedures, but the method to be used here is the four-point implicit method first used by Preissman (1961) with subsequent applications by, among others, Amein and Fang (1970) and Amein and Chu (1975). This formulation is the most widely used and accepted method presently available. The method is weighted implicit at each time level, is unconditionally stable for $0.5 < \theta \leq 1.0$, and permits relatively unequal space and time-steps. The scheme has second-order accuracy when $\theta = 0.5$ and first-order accuracy when $\theta = 1.0$. It is fully nonlinear but yet is a compact scheme requiring just two points at each time level for second-order spatial accuracy.

The river system is discretized (Figure 6-1) by a network of time and space nodes separated by time and space increments Δx_i , Δt_j . If β denotes the point about which the governing equation is to be discretized, then the values of the variables at the four points surrounding β are used to form the appropriate derivatives and weighted averages.

For a general variable ω , then

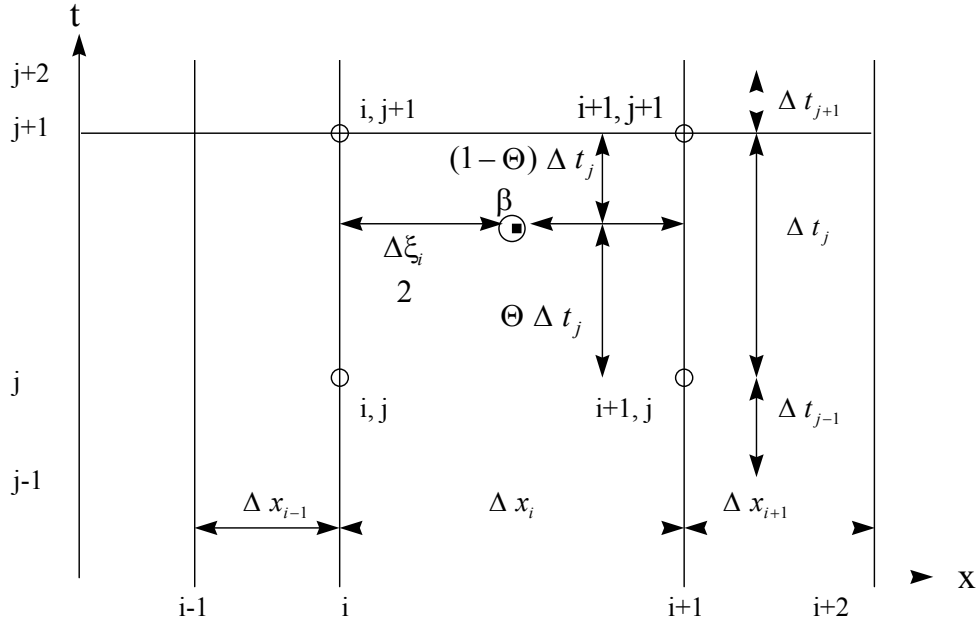


Figure 6-1

$$\omega(\beta) \cong \theta \left(\frac{\omega_i^{j+1} + \omega_{i+1}^{j+1}}{2} \right) + (1 - \theta) \left(\frac{\omega_i^j + \omega_{i+1}^j}{2} \right)$$

Equation 6-27

$$\frac{\partial \omega(\beta)}{\partial x} \cong \theta \left(\frac{\omega_{i+1}^{j+1} - \omega_i^{j+1}}{\Delta x_i} \right) + (1 - \theta) \left(\frac{\omega_{i+1}^j - \omega_i^j}{\Delta x_i} \right)$$

Equation 6-28

$$\frac{\partial \omega(\beta)}{\partial t} \cong \left(\frac{\omega_i^{j+1} + \omega_{i+1}^{j+1}}{2 \Delta t_j} \right) - \left(\frac{\omega_i^j + \omega_{i+1}^j}{2 \Delta t_j} \right)$$

Equation 6-29

6.3.3. Application to Governing Equations

6.3.3.1. THE CONTINUITY EQUATION

The continuity equation is

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q = 0$$

Equation 6-30

Using the definitions in Equations Equation 6-27 to Equation 6-29, the discretized form of this equation is

$$\begin{aligned} & \frac{1}{2\Delta t_j} \left[(A + A_o)_i^{j+1} + (A + A_o)_{i+1}^{j+1} - (A + A_o)_i^j - (A + A_o)_{i+1}^j \right] \\ & + \theta \left[\frac{1}{\Delta x_i} (Q_{i+1}^{j+1} - Q_i^{j+1}) \right] - \theta \frac{(q_{i+1}^{j+1} + q_i^{j+1})}{2} \\ & + (1 - \theta) \left[\frac{1}{\Delta x_i} (Q_{i+1}^j - Q_i^j) \right] - (1 - \theta) \frac{(q_{i+1}^j + q_i^j)}{2} \\ & = F_i(Q_{i+1}, A_{i+1}, Q_i, A_i) = 0 \end{aligned}$$

Equation 6-31

6.3.3.2. THE MOMENTUM EQUATION

The numerical discretization of the momentum equation is

$$\begin{aligned}
& \frac{1}{2\Delta t_j} (Q_i^{j+1} + Q_{i+1}^{j+1} - Q_i^j - Q_{i+1}^j) \\
& + \left\{ \theta \frac{I}{\Delta x_i} \left[\left(\frac{Q^2}{A} \right)_{i+1}^{j+1} - \left(\frac{Q^2}{A} \right)_i^{j+1} \right] + \theta g \left(\frac{A_{i+1}^{j+1} + A_i^{j+1}}{2} \right) \left[\frac{I}{\Delta x_i} (h_{i+1}^{j+1}) \right] \right. \\
& + \frac{g\theta}{2(2.2)} \left[\left(\frac{n_{i+1}^2 |Q_{i+1}| Q_{i+1}}{A_{i+1} R_{i+1}^{4/3}} \right)^{j+1} + \left(\frac{n_i^2 |Q_i| Q_i}{A_i R_i^{4/3}} \right)^{j+1} \right] \\
& - \theta g \left(\frac{A_{i+1}^{j+1} + A_i^{j+1}}{2} \right) \left(\frac{S_{o_{i+1}} + S_{o_i}}{2} \right) \\
& + \theta \left(\frac{A_{i+1}^{j+1} + A_i^{j+1}}{8} \right) \frac{K_E}{\Delta x_i} \left[\left(\frac{Q^2}{A^2} \right)_{i+1}^{j+1} + \left(\frac{Q^2}{A^2} \right)_i^{j+1} \right] \Big\} \\
& - \theta \left(\frac{q_{i+1}^{j+1} + q_i^{j+1}}{2} \right) \left(\frac{U_{q_{i+1}}^{j+1} + U_{q_i}^{j+1}}{2} \right) \\
& + (1 - \theta) \left\{ \frac{1}{\Delta x_i} \left[\left(\frac{Q^2}{A} \right)_{i+1}^j - \left(\frac{Q^2}{A} \right)_i^j \right] + g(1 - \theta) \left(\frac{A_{i+1}^j + A_i^j}{2} \right) \left[\frac{1}{\Delta x_i} (h_{i+1}^j - h_i^j) \right] \right. \\
& + \frac{g(1 - \theta)}{2(2.2)} \left[\left(\frac{n_{i+1}^2 |Q_{i+1}| Q_{i+1}}{A_{i+1} R_{i+1}^{4/3}} \right)^j + \left(\frac{n_i^2 |Q_i| Q_i}{A_i R_i^{4/3}} \right)^j \right] \\
& - g(1 - \theta) \left(\frac{A_{i+1}^j + A_i^j}{2} \right) \left(\frac{S_{o_{i+1}} + S_{o_i}}{2} \right) \\
& + (1 - \theta) \left(\frac{A_{i+1}^j + A_i^j}{8} \right) \frac{K_E}{\Delta x_i} \left[\left(\frac{Q^2}{A^2} \right)_{i+1}^j + \left(\frac{Q^2}{A^2} \right)_i^j \right] \Big\} \\
& - (1 - \theta) \left(\frac{q_{i+1}^j + q_i^j}{2} \right) \left(\frac{U_{q_{i+1}}^j + U_{q_i}^j}{2} \right) \\
& = G_i(Q_{i+1}, A_{i+1}, Q_i, A_i) = 0
\end{aligned}$$

Equation 6-32

6.3.3.3. THE BOUNDARY CONDITIONS

The boundary conditions must also be "discretized." This is accomplished as follows. For example, the discretized form of the upstream boundary in terms of A becomes

$$F_o = A_l^{j+1} - A_u(t^{j+1}) = 0$$

Equation 6-33

while the downstream boundary condition at node N becomes

$$F_N = A_N^{j+1} - A_d(t^{j+1}) = 0$$

Equation 6-34

If flows or discharges are to be specified, then the upstream boundary condition becomes

$$F_o = Q_l^{j+1} - Q_u(t^{j+1}) = 0$$

Equation 6-35

and the downstream condition is

$$F_N = Q_N^{j+1} - Q_d(t^{j+1}) = 0$$

Equation 6-36

6.3.3.4.EQUATION ASSEMBLY

Equations F_i (Equation 6-31) and G_i (Equation 6-32) are applied at every node i on both the main stem and any included tributaries. The system of algebraic equations results in $2N-2$ equations for $2N$ unknowns. The two boundary conditions are sufficient to completely close the problem. If $G_0(Q_1, A_1)$ and $G_N(Q_N, A_N)$ are the boundary conditions written in the form of Equation 6-33 to Equation 6-36, then the resulting system of $2N$ nonlinear equations is formally written as:

$$G_0(Q_1, A_1) = 0$$

$$F_1(Q_2, A_2, Q_1, A_1) = 0$$

$$G_1(Q_2, A_2, Q_1, A_1) = 0$$

.....

.....

$$F_i(Q_{i+1}, A_{i+1}, Q_i, A_i) = 0$$

$$G_i(Q_{i+1}, A_{i+1}, Q_i, A_i) = 0$$

.....

.....

$$F_{N-1}(Q_N, A_N, Q_{N-1}, A_{N-1}) = 0$$

$$G_{N-1}(Q_N, A_N, Q_{N-1}, A_{N-1}) = 0$$

$$G_N(Q_N, A_N) = 0$$

Equation 6-37



The general solution of these nonlinear equations is obtained using a Newton-Raphson iteration procedure.

6.3.3.5. *NEWTON-RAPHSON SOLUTION FOR FLOW AND ELEVATION*

The Newton-Raphson method for nonlinear systems is based upon estimating the residuals from each algebraic equation introduced by assuming initial answers for Q_i and A_i . The iterative reduction of the residuals by successive Taylor series refinement of the estimates of Q_i and A_i completes the procedure. Details of Newton's method can be found in Burden and Faires (1989). The generalized Newton-Raphson procedure must be performed at each time-step. This method has been used with excellent success by the previously cited authors.

However, unlike the procedures by these authors, the formulation herein employs a direct simultaneous solution at each iteration for all of the flows and elevations in both main stem and tributaries. Previous methods employed an iterative method of estimating such variables. Therefore, for each Newton-Raphson iteration, another sequence of interior iterations was performed. The formulation herein requires only one five-band matrix solution at each Newton-Raphson iteration.

The residuals, $R_{1,i}^k$ and $R_{2,i}^k$, from the k^{th} estimate of Q_i and A_i are found for Equations

$$G_0(Q_1^k, A_1^k) = R_{2,0}^k$$

$$F_1(Q_2^k, A_2^k, Q_1^k, A_1^k) = R_{1,1}^k$$

$$G_1(Q_2^K, A_2^K, Q_1^K, A_1^K) = R_{2,1}^k$$

.....

.....

$$F_i(Q_{i+1}^k, A_{i+1}^k, Q_i^k, A_i^k) = R_{1,i}^k$$

$$G_i(Q_{i+1}^k, A_{i+1}^k, Q_i^k, A_i^k) = R_{2,i}^k$$

.....

.....

$$F_{N-1}(Q_N^k, A_N^k, Q_{N-1}^k, A_{N-1}^k) = R_{1,N-1}^k$$

$$G_{N-1}(Q_N^k, A_N^k, Q_{N-1}^k, A_{N-1}^k) = R_{2,N-1}^k$$

$$G_N(Q_N^k, A_N^k) = R_{2,N}^k$$

Equation 6-38

F_i and G_i as

A generalized Taylor series for a function T that is a function of four dependent variables, S_1 , S_2 , S_3 , and S_4 is written as

$$T^{k+1} = T^k + \frac{\partial T}{\partial S_1} dS_1 + \frac{\partial T}{\partial S_2} dS_2 + \frac{\partial T}{\partial S_3} dS_3 + \frac{\partial T}{\partial S_4} dS_4$$

Equation 6-39

This general form is now used to relate the residuals to the gradients as follows. Keep in mind that we want to drive the residuals to zero; thus we want F_i and G_i to be zero. If T^{k+1} represents the exact solution for F_i or G_i , then T^{k+1} is zero. This means that the unknowns are dS_1 , dS_2 , dS_3 , and dS_4 . Let T^k be the R_{ji}^k residual. Further, assume that S_1 , S_2 , S_3 , and S_4 become the values Q_{i+1} , A_{i+1} , Q_i , and A_i . In the Newton-Raphson iteration, the gradients are known from the k^{th} estimate of Q_i and A_i , and the relationship between the gradients and the residuals becomes

$$\frac{\partial G_0}{\partial A_1} dA_1 + \frac{\partial G_0}{\partial Q_1} dQ_1 = R_{2,0}^k$$

$$\frac{\partial F_1}{\partial Q_2} dQ_2 + \frac{\partial F_1}{\partial A_2} dA_2 + \frac{\partial F_1}{\partial Q_1} dQ_1 + \frac{\partial F_1}{\partial A_1} dA_1 = R_{1,1}^k$$

$$\frac{\partial G_1}{\partial Q_2} dQ_2 + \frac{\partial G_1}{\partial A_2} dA_2 + \frac{\partial G_1}{\partial Q_1} dQ_1 + \frac{\partial G_1}{\partial A_1} dA_1 = R_{2,1}^k$$

.....

.....

$$\frac{\partial F_i}{\partial Q_{i+1}} dQ_{i+1} + \frac{\partial F_i}{\partial A_{i+1}} dA_{i+1} + \frac{\partial F_i}{\partial Q_i} dQ_i + \frac{\partial F_i}{\partial A_i} dA_i = R_{1,i}^k$$

$$\frac{\partial G_i}{\partial Q_{i+1}} dQ_{i+1} + \frac{\partial G_i}{\partial A_{i+1}} dA_{i+1} + \frac{\partial G_i}{\partial Q_i} dQ_i + \frac{\partial G_i}{\partial A_i} dA_i = R_{2,i}^k$$

.....

$$\frac{\partial F_{N-1}}{\partial Q_N} dQ_N + \frac{\partial F_{N-1}}{\partial A_N} dA_N + \frac{\partial F_{N-1}}{\partial Q_{N-1}} dQ_{N-1} + \frac{\partial F_{N-1}}{\partial A_{N-1}} dA_{N-1} = R_{1,N-1}^k$$

$$\frac{\partial G_{N-1}}{\partial Q_N} dQ_N + \frac{\partial G_{N-1}}{\partial A_N} dA_N + \frac{\partial G_{N-1}}{\partial Q_{N-1}} dQ_{N-1} + \frac{\partial G_{N-1}}{\partial A_{N-1}} dA_{N-1} = R_{2,N-1}^k$$

$$\frac{\partial G_N}{\partial Q_N} dQ_N + \frac{\partial G_N}{\partial A_N} dA_N = R_{2,N}^k$$

Equation 6-40

where the minus sign (from moving T^k to the other side of the equation) has been included in the residuals; thus the residuals are the negative of Equation 6-31 and Equation 6-32. Note that all derivatives are taken with

respect to Q_{i+1}^{j+1} , A_{i+1}^{j+1} , Q_i^{j+1} , A_i^{j+1} , etc. Additionally, for all Q_i and A_i evaluated at time $j+1$

$$dQ_1 = Q_1^{k+1} - Q_1^k$$

$$dA_1 = A_1^{k+1} - A_1^k$$

.....

.....

$$dQ_i = Q_i^{k+1} - Q_i^k$$

$$dA_i = A_i^{k+1} - A_i^k$$

.....

.....

$$dQ_N = Q_N^{k+1} - Q_N^k$$

$$dA_N = A_N^{k+1} - A_N^k$$

Equation 6-41

The derivatives of F_i and G_i with respect to A_{i+1}^{j+1} , Q_{i+1}^{j+1} , A_i^{j+1} , and Q_i^{j+1} are found from Equation 6-31 and Equation 6-32 as follows:

$$\frac{\partial F_i}{\partial A_i^{j+1}} = \frac{1}{2\Delta t_j}$$

$$\frac{\partial F_i}{\partial Q_i^{j+1}} = \frac{\theta}{\Delta x_i}$$

$$\frac{\partial F_i}{\partial A_{i+1}^{j+1}} = \frac{1}{2\Delta t_j}$$

$$\frac{\partial F_i}{\partial Q_{i+1}^{j+1}} = \frac{\theta}{\Delta x_i}$$

Equation 6-42

and

$$\frac{\partial G_i}{\partial Q_i^{j+1}} = \frac{l}{2\Delta t_j} + \theta \left[\frac{-2}{\Delta x_i} \frac{Q_i^{j+1}}{A_i^{j+1}} + \frac{g}{2(2.2)} \frac{n_i^2 |Q_i^{j+1}|}{A_i^{j+1} (R_i^{j+1})^{4/3}} \right. \\ \left. + 2 \left(\frac{A_{i+1}^{j+1} + A_i^{j+1}}{8\Delta x_i} \right) K_E \frac{Q_i^{j+1}}{(A_i^{j+1})^2} \right]$$

Equation 6-43

$$\frac{\partial G_i}{\partial Q_{i+1}^{j+1}} = \frac{l}{2\Delta t_j} + \theta \left[\frac{2}{\Delta x_i} \frac{Q_{i+1}^{j+1}}{A_{i+1}^{j+1}} + \frac{g}{2(2.2)} \frac{n_{i+1}^2 |Q_{i+1}^{j+1}|}{A_{i+1}^{j+1} (R_{i+1}^{j+1})^{4/3}} \right. \\ \left. + 2 \left(\frac{A_{i+1}^{j+1} + A_i^{j+1}}{8\Delta x_i} \right) K_E \frac{Q_{i+1}^{j+1}}{(A_{i+1}^{j+1})^2} \right]$$

Equation 6-44

$$\begin{aligned}
\frac{\partial G_i}{\partial A^{j+1}} = & \theta \left\{ \frac{1}{\Delta x_i} \left(\frac{Q^2}{A^2} \right)_i^{j+1} + \frac{g}{2\Delta x_i} \left[\left(h_{i+1}^{j+1} - h_i^{j+1} \right) - \frac{(A_{i+1}^{j+1} + A_i^{j+1})}{B_i^{j+1}} \right] \right. \\
& + \frac{gn_i^2}{6(2.2)} \frac{|Q_i^{j+1}| Q_i^{j+1}}{A_i^{j+1} (R_i^{j+1})^{4/3}} \left[\frac{-7}{A_i^{j+1}} + \frac{4 \frac{dB}{dh} \Big|_i^{j+1}}{(B_i^{j+1})^2} + \frac{6 \frac{\partial n}{\partial h} \Big|_i}{n_i B_i^{j+1}} \right] \\
& \left. - \frac{g}{2} \left(\frac{S_{o_{i+1}} + S_{o_i}}{2} \right) + \frac{K_E}{8\Delta x_i} \left[\left(\frac{Q^2}{A^2} \right)_{i+1}^{j+1} - \left(\frac{Q^2}{A^2} \right)_i^{j+1} \left(1 + \frac{2 A_{i+1}^{j+1}}{A_i^{j+1}} \right) \right] \right\}
\end{aligned}$$

Equation 6-45

$$\begin{aligned}
\frac{\partial G_i}{\partial A_{i+1}^{j+1}} = & \theta \left\{ \frac{-1}{\Delta x_i} \left(\frac{Q^2}{A^2} \right)_{i+1}^{j+1} + \frac{g}{2\Delta x_i} \left[\left(h_{i+1}^{j+1} - h_i^{j+1} \right) + \frac{(A_{i+1}^{j+1} + A_i^{j+1})}{B_{i+1}^{j+1}} \right] \right. \\
& + \frac{gn_{i+1}^2}{6(2.2)} \frac{|Q_{i+1}^{j+1}| Q_{i+1}^{j+1}}{A_{i+1}^{j+1} (R_{i+1}^{j+1})^{4/3}} \left[\frac{-7}{A_{i+1}^{j+1}} + \frac{4 \frac{dB}{dh} \Big|_{i+1}^{j+1}}{(B_{i+1}^{j+1})^2} + \frac{6 \frac{\partial n}{\partial h} \Big|_{i+1}}{n_{i+1} B_{i+1}^{j+1}} \right] \\
& \left. - \frac{g}{2} \left(\frac{S_{o_{i+1}} + S_{o_i}}{2} \right) + \frac{k_E}{8\Delta x_i} \left[\left(\frac{Q^2}{A^2} \right)_i^{j+1} - \left(\frac{Q^2}{A^2} \right)_{i+1}^{j+1} \left(1 + \frac{2 A_i^{j+1}}{A_{i+1}^{j+1}} \right) \right] \right\}
\end{aligned}$$

Equation 6-46

The following subsidiary manipulations have been used. First, area and depth gradients are related by the equation $\partial A / \partial z = B \partial h / \partial x$ and second, the hydraulic radius is approximately equal to the hydraulic depth or

$R = A/B$. In EPD-RIV1, an explicit relationship between A and h may be used of the form.

$$A = a_{0h} + a_1 h^{a_2}$$

Equation 6-47

By appropriate selection of the coefficients (a_0 , a_1 , a_2), most regularly formed channel cross sections can be modeled by this function. Alternatively, EPD-RIV1 will develop relationships between depth and areas using information supplied in look up tables.

6.3.3.6. CALCULATION PROCEDURE

The nonlinear solution procedure is used to calculate the new flows Q_i^{j+1} and areas A_i^{j+1} as follows:

- 1) Assume Q_i^j that
 A_i^j and
 i are known either from initial conditions or from the completion of the previous Newton- Raphson solution.
- 2) By insertion of Q_i^j and A_i^j into the equations for F and G , form the $k = 1$ residuals R_{ji}^1 , by assuming that $k = 1$ estimate for $Q_i^{j+1,k}$ and $A_i^{j+1,k}$ is the j^{th} time-step value for Q and A or the initial condition (Step 1). For $k > 1$, the previous k^{th} estimates of Q_i^{j+1} and A_i^{j+1} are used.
- 3) After forming the residuals, the gradients are formed from Equation 6-42 to Equation 6-46, again by using the $k = 1$ estimates for Q and A . For subsequent iterations, the previous k^{th} estimates are used.
- 4) From Equation 6-40 and Steps 1 through 3, a coefficient matrix is formed and assembled; a system of linear simultaneous equations $[M]^k \{D\}^k = \{R\}^k$ is solved for $\{D\}^k$.

- 5) When solved for, the departure vector $\{D\}^k$ is added to the old estimates of Q and A , to give a new estimate for Q and A , i.e.

$$Q_i^{j+1,k+1} = Q_i^{j+1,k} + dQ_i^k$$

and

$$A_i^{j+1,k+1} = A_i^{j+1,k} + dA_i^k$$

A check is made to see how close $Q_i^{j+1,k+1}$ and $A_i^{j+1,k+1}$ are to $Q_i^{j+1,k}$ and $A_i^{j+1,k}$

and if the largest difference is less than some specified tolerance, the iteration stops and the new values of A and Q for the $j+1$ time-steps are at hand. If the tolerance is exceeded, return to Step 2 and using $Q_i^{j+1,k+1}$ and $A_i^{j+1,k+1}$, repeat Steps 2 through 6.

7. WATER QUALITY

7.1. Governing Equation

The general form of the equation to be solved is, for a mass concentration α ,

$$\frac{\partial \alpha}{\partial t} + u \frac{\partial \alpha}{\partial x} = D \frac{\partial^2 \alpha}{\partial x^2} + \frac{q}{A}(\gamma - \alpha) - K_s \alpha + \text{SINKS}$$

Equation 7-1

where

u = velocity
 x = longitudinal distance
 q = lateral inflow rate
 D = dispersion coefficient

γ = concentration of the runoff input to the channel by distributed flow q
 K_s = biochemical uptake or decay rates (+) and growth rates (-)
SINKS = biochemical sources (+) and sinks (-)

The first term on the left hand side of the above equation represents the time rate of change of constituent concentration. The second term represents advection of the constituent. On the right hand side, the terms represent diffusion, lateral loadings (or withdrawals), reactions and sources/sinks. The reactions are those affecting the particular constituent, such as decay or decomposition. The source and sink terms may represent sources from other constituents (e.g. the nitrification is a reaction term for ammonia and a source term for nitrate) or external sources (e.g. surface heat exchange is a source term for temperature).

The above equation applies to all water quality constituents. What defines a particular constituent are the concentrations assigned to the boundaries and lateral inflows and the number and kind of reactions and sources/sinks. The transport variables (velocities, flows, areas, etc.) are common to all water quality constituents.

The left side of the above equation is solved for the new time level value using a fourth-order explicit scheme. Using this new value, the concentration is incremented due to the effects of the second, third, and fourth terms on the right side of the above equation. The SINKS and K_s values are interpolated values between nodes. Finally, the solution is completed by adding the effect of diffusion (first term on right side of the above equation), which is computed implicitly. A detailed discussion of the development of this equation and of the solution scheme may be found in Section 7.4.

7.2. Transport Relationships

The two primary transport processes affecting constituent concentrations in Equation 7-1 are advection and diffusion. The hydrodynamic equations solved by EPD-RIV1 for flow and elevation are not affected by constituent concentration. Since the hydrodynamics are independent of the constituent concentrations, a complete prediction of flows, areas, and other hydraulic characteristics can then be made without one's solving for the constituents. This allows the hydrodynamic model to be separated from the quality model. The hydrodynamic model can be run and its predictions saved in a file, **the hydrodynamic linkage file**. This provides

economy since it is not necessary to rerun the hydrodynamics for every quality simulation. An overview of the structure of the linkage file is provided below.

The hydrodynamic linkage file provides information on advection and hydraulic characteristics to the quality model. Dispersion, on the other hand, is not considered in the hydrodynamic equations. Rates of dispersion are specified by the user in the quality input file and may be varied by model node.

7.2.1. Advection and Geometry: The Hydrodynamic Linkage File

Although, the hydrodynamics and quality model are run separately, their segmentation schemes, or model grid, must be the same. The hydrodynamic linkage file contains information on the run time controls and the geometric set up, including the

- Start and end times for the hydrodynamic simulation,
- Number of branches and number of nodes,
- The ordering system of the nodes and linkages, as determined by the hydrodynamic code,
- Channel lengths, constant lateral inflows, river miles and roughness coefficients.

This information does not change with time and is written at the beginning of the linkage file. Note that:

- The user does not specify any of the geometric information in the quality input file, it must be based upon the set-up of the hydrodynamics simulation. Therefore the files must correspond in terms of the number of branches and nodes.
- Start times and end times for the quality run do not have to be the same as, but must fall within the range of, those of the hydrodynamic run.

For each time step of the hydrodynamic simulation, the linkage file contains the

- time step, and for each node the
- flow,
- time-varying lateral inflow,
- cross-sectional area, and
- width.

Thus all of the geometric information, and information necessary to compute advection, is contained in the linkage file. The information is passed in the linkage file in English Units and then converted to metric units for use by RIV1Q. Some of the information is (flows, elevations) converted back to English units in model output.

7.2.2. Dispersion

Dispersion is used in one-dimensional models to represent the combined effect of turbulent diffusion and the smearing of concentrations due to non-uniformities in the velocity distribution over the cross-section. If dispersion was not specified, and the model accurately advected the material, then it would move downstream as a slug. In natural systems, however, the impact of non-uniformities and turbulence would cause some materials to move ahead, and some behind, the centroid of the mass. For example, a dye cloud would move downstream at the mean velocity but some of the dye would spread out in front of and behind the centroid of the dye cloud. The processes affecting this spreading are represented in EPD-RIV1 using dispersion coefficients. The expression used to compute the rate of dispersion ($D, \text{m}^2 \text{sec}^{-1}$) is based upon a time-invariant rate to which is added the effects of the mean velocity and hydraulic depth, as

$$D = D_0 + g^{0.5} k_D n |u| \left(\frac{A}{B} \right)^{\frac{5}{6}}$$

Equation 7-2

where

D_0	=	constant (time-invariant) rate of dispersion ($\text{m}^2 \text{sec}^{-1}$)
k_D	=	dispersion coefficient
g	=	gravitational acceleration (9.817 m s^{-2})
n	=	roughness coefficient (Manning's n ; from linkage file)
A	=	cross-sectional area (m^2)
B	=	width (m)

The roughness coefficient, areas, and widths are obtained from the hydrodynamic linkage file. The values of **D_0 and k_D are input by the user for each node.** Note that in the above relationship **D_0 is provided in input in units of $\text{ft}^2 \text{sec}^{-1}$** and then converted by RIV1Q to metric units. The time-invariant rate of dispersion and dispersion coefficient may be varied by model node. The above equation allows the user to specify a time-invariant rate of dispersion for each node ($D_0 \neq 0$, $k_D = 0$), have the model compute it ($D_0 = 0$, $k_D \neq 0$), or a combination of the two ($D_0 \neq 0$, $k_D \neq 0$).

The value of the dispersion rate is highly variable, ranging from a few to hundreds of $\text{ft}^2 \text{sec}^{-1}$. Its values are best determined through dye studies or during model calibration. There are also a variety of formulations that have been proposed to compute the rate of dispersion, and the one included in EPD-RIV1 is based upon that used by QUAL-2E (Brown and Barnwell 1987). The k_D is a coefficient relating longitudinal dispersion to depth and velocity shear (see Brown and Barnwell 1987) using Elder's (1959) relationship. Elder used a value of 5.93 in his studies. Fischer et al. (1979) indicated that longitudinal dispersion in real streams is almost always greater than that predicted using Elder's equation. Brown and Barnwell (1987) provide values for the dispersion constant (k_D) ranging from 8.6 (South Platte River) to 7500 (for the Missouri River).

7.2.3. Lateral Inflows, Withdrawals and Power Cross-Sections

The flow rates for the lateral inflows are passed in the hydrodynamic linkage file. The constituent concentrations associated with those flows are read by EPD-RIV1Q. The lateral flows from the hydrodynamic linkage file and constituent concentrations are used to determine the rate of mass

loading. The rates of withdrawal are not used by RIV1Q. The effect of the withdrawal is included in the hydraulic variables contained in the linkage file. The effect of the withdrawal is not to reduce concentration at the point of the withdrawal, but to remove constituent mass along with the water mass. For the power cross-sections, both a flow and a temperature are specified. The temperatures may represent either an effluent temperature or a increment in temperature of the effluent above ambient. The flows specified are used to compute a heat load and do not impact the transport computations.

7.3. Water Quality Kinetics

The constituent transport relationships discussed previously (Section 7.1) are used to compute the transport of constituents with their kinetics expressed in reaction rates and source and sink terms. In this section, the mathematical formulations of the sources, sinks, and reaction kinetics for the various water quality components are presented. The most significant of these are temperature and DO. However, other variables are also included because of their effect on DO. These variables include carbonaceous biochemical oxygen demand (CBOD) as well as nitrogen and phosphorous compounds. The growth and decay of algae and macrophytes are also modeled to complete the DO balance. Algae is modeled as a state variable (subject to advective and dispersive transport) but macrophytes are not. Nitrite plus nitrate-nitrogen is included to complete the nitrogen cycle. Organic and phosphate-phosphorus are modeled to complete the phosphorous cycle. Coliform bacteria are included as a state variable because of their importance in stream pollution. Dissolved iron and manganese are included because of their impact on DO in streams below dams with anoxic hypolimnetic releases. Two arbitrary constituents are also included to allow simulation of dyes or other materials. Thus, 16 modeled variables are included:

-
- | | | |
|----------------------|----------------|------------------------------|
| • Temperature | • Ortho-P | • CBOD-2 |
| • CBOD | • Dissolved Mn | • NBOD |
| • Organic-N | • Dissolved Fe | • Arbitrary
Constituent 1 |
| • NH ₃ -N | • DO | • Arbitrary
Constituent 2 |
| • NO ₃ -N | • Coliforms | |
| • Organic-P | • Algae | |

and those to be modeled are selected by the user. **All of the state variables may be simulated or "bypassed."** If the user elects to bypass a particular state variable (using the bypass options as described in Part VII, then the concentrations will be held to those specified in the initial conditions for the duration of the simulation.

7.3.1. Temperature

It is often necessary to account for the effects of temperature changes along a channel in order to account for temperature gradients created by cultural inputs such as power plant effluents or natural processes. In addition to its intrinsic value, temperature information is required in order to correct kinetic rate coefficients. Stream temperatures may be read in directly or may be calculated/predicted from the solution of an appropriate thermal energy balance.

The transport equation developed in Section 7.1 is used to solve for each water quality variable, α ; thus for temperature, $\alpha \equiv T$. The specification of the source/sink term and the decay term must account for all the mechanisms other than advection, diffusion, and lateral inflows, which cause net transfers of energy to the control volume. There are two approaches implemented in EPD-RIV1 for computing water temperatures, the heat balance approach and the equilibrium temperature approach, and each is described below.

7.3.1.1. HEAT BALANCE APPROACH

In general, the heat balance approach used here is the same as that used in the QUAL2E model (Brown and Barnwell 1987). The external sources and sinks (excluding lateral inflows) for heat are described by

$$H_N = H_S (1 - C_s) + H_L - H_E - H_B \pm H_C$$

Equation 7-3

where__

H_N	=	net heat transfer, heat energy surface area ⁻¹ time ⁻¹
H_S	=	net short-wave radiation
H_L	=	net long-wave radiation
H_E	=	heat loss because of evaporation
H_B	=	heat loss because of back radiation of the water
H_C	=	heat transferred by conduction at the water surface and the bottom

and C_s is a canopy shading coefficient. In the full heat balance, each of the above terms is computed and added to determine the net heat exchange, H_N , which is converted to a rate of temperature change by

$$\dot{\Delta T} = \frac{H_N}{\rho C_p H} \bullet \text{conv}$$

Equation 7-4

where

ΔT	=	rate of temperature change, (degrees time ⁻¹)
ρ	=	density of water (mass volume ⁻¹)
C_p	=	specific heat of water (heat energy mass ⁻¹ degree ⁻¹)
H	=	hydraulic depth (Area/Top Width, length)
conv	=	conversion factor from English to metric units (computations are performed in English units).

The computations for the heat flux terms depend on the:

- water temperature, T_s ,
- time of year and day,

- site latitude,
- longitude,
- elevation, and
- local meteorological data.

The meteorological data necessary for the computation consist of

- air and dew point temperatures ($^{\circ}\text{C}$),
- wind speed,
- cloud cover,
- and barometric pressure.

Generally, meteorological data are collected and reported in 1- or 3-hr intervals. This method is referred to as a direct energy balance because independent determination of each of the heat balance terms is made within the simulation, in contrast to the alternative heat exchange method. The reader is referred to Brown and Barnwell (1987) for a complete development of the terms in the heat balance.

The user may specify up to five meteorological input files, allowing for different conditions along the study reach. In each file the user specifies the range of nodes to which the file applies.

7.3.1.2.EQUILIBRIUM TEMPERATURE APPROACH

The alternative method uses the equilibrium temperature approach, as developed by Edinger and Geyer (1965) and Edinger, Brady, and Geyer (1974), to account for the effects of surface heating and radiation. The equilibrium temperature approach is based on the concept that heat exchange does not occur when the water temperature, T_S , equals the equilibrium temperature, T_E ; thus, $H_N = 0$. With $T_S = T_E$ and $H_N = 0$, the terms on the right side of Equation 106 can be expressed in terms of T_E , and T_E can be solved iteratively. Net heat transfer, H_N , is computed from

$$H_N = K_E (T_E - T_S)$$

Equation 7-5

where K_E is the heat exchange coefficient (heat energy/surface area/time/degree). Using a computer program with the same meteorological data used for the direct energy balance, T_E and K_E are computed independent of the simulation. This program can be obtained from WES or the Hydrologic Engineering Center (HEC). A description of the T_E and K_S computation is given in Edinger, Brady, and Geyer (1974).

If the equilibrium temperature approach is followed, the model uses a single, constant value for T_E and K_E . This is equivalent to modeling stream temperature under constant meteorological conditions. The computations of T_E and K_E in the WES and HEC program are based on daily average values for meteorological data; thus daily average values of T_E and K_E are produced. Daily average values for T_E and K_E may not be adequate for applications where diel fluctuations are important. In these cases, the direct energy balance method should be used.

By inspection of Equation 7-5, the K_S coefficient of Equation 7-1 is K_E (KTS in the code) and the SINKS term is $K_E T_E$ (KTS*TEQ in code). Thus, KTS is converted to units of per time (per day) by dividing by $(\rho c_p H)$ with the proper conversion units.

7.3.1.3. BOTTOM HEAT EXCHANGE

Either heat exchange method can be augmented with bottom heat transfer by adding the term $K_B (TSINK - T_S)$ where TSINK is the bottom/ground temperature in degrees and K_B is the bottom heat transfer coefficient in units of per day. In this case, K_B and TSINK must be specified, the K_S term of Equation 7-1 is incremented by K_B (KTB in the code), and the SINKS term of Equation 7-1 is incremented by $K_B * TSINK$.

7.3.1.4. PARAMETERS AND CONSTANTS FOR WATER TEMPERATURE

1) Parameters that can appear in the Global Constants Cards			
Name	Explanation	Typical Value	Reference

ITEM	Variable designating type of heat exchange solution	1= equilibrium, 0 = full heat balance	-
IPOW	Power Plant Option	0= no 1 = yes)	-
TH_BHEAT	Temperature coefficient for bottom heat exchange		-

2) Parameters that can appear in the Branch Constants Cards

Name	Explanation	Typical Value	Reference
TEMP	Stream segment equilibrium temperature, °C (needed if ITEM = 1)	variable	-
ATS	Rate coefficient for surface heat exchange, $W\ m^{-2}\ ^\circ C^{-1}$ (Needed if ITEM=1)	variable	
ATB	Rate coefficient for bottom heat exchange, day^{-1}	variable	
TSINK	Source/sink term for bottom heat exchange, °C	variable	

3) Parameters that vary by node

Name	Explanation	Typical Value	Reference
CANOPY	Canopy Shading Coefficient	0 to 1	

7.3.2. Biochemical Oxygen Demand

7.3.2.1. CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND (TYPES 1 AND 2)

The CBOD represents (as chemically equivalent oxygen) the ultimate amount of biodegradable organic matter present, excluding organic nitrogen. That is, **the state variable for CBOD is the ultimate CBOD (not BOD₅)**. All concentrations for boundary conditions and lateral

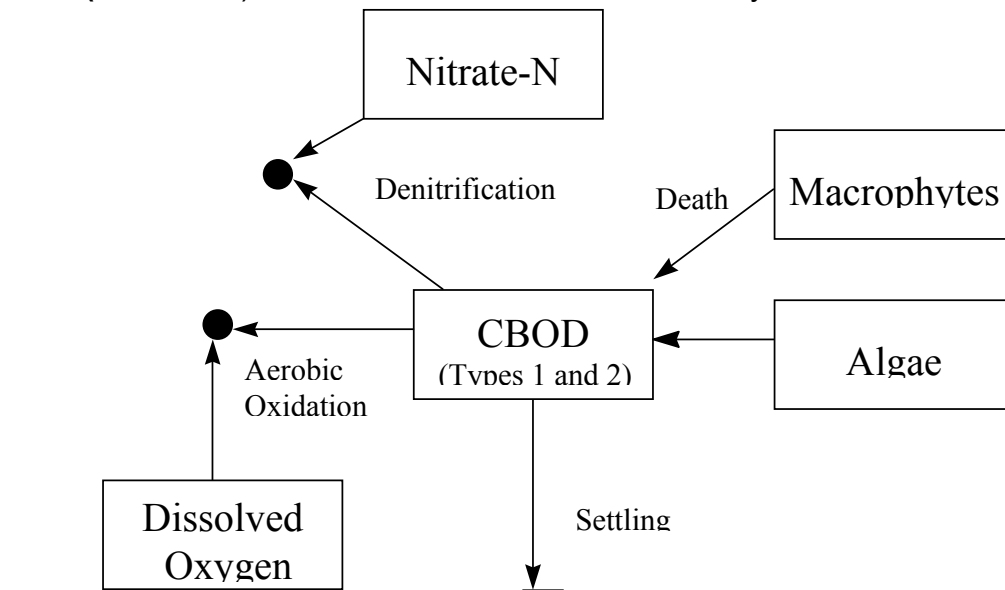


Figure 7-1

inflows should be ultimate CBOD values.

There are two state variables for CBOD. Both are treated similarly, with similar kinetics. However, separate rate terms and coefficients are provided for each of the two forms.

CBOD is a result of biochemical oxidation of organics by heterotrophic bacteria using either oxygen or nitrate as the terminal electron acceptor. The latter process is called denitrification. In this model, it is assumed that oxygen is the terminal electron acceptor at high DO's and nitrate at low DO's. Thus, the basic reaction for CBOD is

$$\left(\begin{array}{c} \text{Rate of CBOD loss due to} \\ \text{oxidation and settling} \\ \text{g/m}^3 / \text{day} \end{array} \right) = - \left(K1 + KDN + \frac{\text{CBODSR}}{H} \right) * \text{CBOD}$$

Equation 7-6

where

- K1 = temperature corrected rate coefficient for aerobic oxidation of CBOD, day⁻¹
- KDN = temperature corrected rate coefficient for nitrate reduction and anaerobic CBOD oxidation, day⁻¹
- CBOD = concentration of CBOD, g O₂/m³, from previous time-step, C(2,I) or C(13,I)
- CBODSR = rate coefficient for CBOD type 1 removal by settling (RBODSR for type 2), m/day
- H = depth, m

A fraction (FCBOD) of decaying algae and macrophytes is assumed to contribute to CBOD, the remainder (1-FCBOD), being oxidized immediately for energy. Also, the reaction rate goes to zero as dissolved oxygen (DO) goes to zero.

$$\left(\begin{array}{c} \text{CBOD gain from} \\ \text{algae/ macrophyte decay} \\ \text{g- BOD/ m}^3 \text{ / day} \end{array} \right) = \frac{\text{OPDECY} * \left(\frac{(\text{FCBOD} * \text{DO}) + \text{KOCB1}}{\text{DO} + \text{KOCB}} \right) *}{(\text{ALGADK} + \text{MDEATH})}$$

Equation 7-7

where

- OPDECY = oxygen-to-biomass ratio for oxygen production by algae and macrophytes when ammonia is nitrogen source,
 FCBOD = fraction of algal and macrophyte mortality contributing to CBOD (FCRBOD for type 2)
 DO = average dissolved oxygen (g/m^3) along the characteristic curve, DOX in the code
 KOCB1 = Monod half velocity constant for oxygen-limited aerobic systems, $\text{g O}_2/\text{m}^3$
 ALGADK = algal death rate (see 7.3.5) $\text{g}/(\text{m}^3\text{day})$
 MDEATH = macrophyte death rate (see 7.3.6), $\text{g}/(\text{m}^3\text{day})$

It should be realized that K_S is $(K1 + \text{KDN} + \text{CBODSR})$, SINKS is the CBOD contribution from algal/macrophyte decay, and α in Equation 7-1 is CBOD..

The rate coefficients $K1$ and KDN are presumed to be functions of the ambient water temperature, the local DO, and the local nitrate concentration. The temperature correction is taken from Streeter and Phelps (1925), as is customary, although arguable. The coefficient $K1$ is assumed to increase with DO according to a simple Monod function (cf. Hoover and Porges 1952), and the coefficient KDN is assumed to decrease according to an analogous formula. The coefficient KDN is also assumed to depend on nitrate in the same way that $K1$ depends on oxygen.

$$K1 = AK1 * [TH_K1^{(TEMP-20.)}] * \left(\frac{DO}{DO + KOCB1} \right)$$

Equation 7-8

$$KDN = ADN * [TH_KDN^{(TEMP-20.)}] * \left(\frac{KOCBDN}{DO + KOCBDN} \right) * \left(\frac{NO_3 - N}{NO_3 - N + KNCBDN} \right)$$

Equation 7-9

where

- AK1, ADN = uncorrected rate coefficients for oxidation and denitrification of CBOD type 1 (KRBOD and ADN2 for type 2), respectively, day⁻¹
 TH_K1 = temperature coefficient for CBOD type 1 (TH_BOD2 for type 2), unitless
 TEMP = T_s = the ambient stream temperature, °C
 DO = local stream oxygen concentration, g O₂/m³
 KOCB1 = Monod half-velocity constant for oxygen-limited systems (RBODDO for type 2), g O₂/m³
 KOCBDN = denitrification inhibition half-velocity constant, g O₂/m³
 NO₃-N = local nitrate-nitrogen concentration, g N/m³
 KNCBDN = Monod half-velocity constant for nitrate-limited denitrification, g N/m³

CBODSR is not corrected for environmental conditions. In addition, no provision for fermentation has been provided, so in the absence of oxygen and nitrate, there is no CBOD removal except through settling.

The net rate of accumulation of CBOD may be written as

$$\left(\begin{array}{c} \text{Net rate of} \\ \text{accumulation} \\ \text{of CBOD} \\ \text{g/ m}^3 \text{ / day} \end{array} \right) = \begin{array}{l} - (\text{AEROBIC OXIDATION OF CBOD}) - (\text{DENITRIFICATION}) \\ - (\text{SETTLING}) + (\text{ALGAE/ MACROPHYTE DECAY}) \end{array}$$

Equation 7-10

and the final equation for CBOD type 1 is

$$= \left(K_1 + K_{DN} + \frac{CBODSR}{H} \right) * CBOD + OPDECY * \frac{(KOCB1 + DOX * FCBOD)}{(DOX + KOCB1)} * (ALGADK + MDEATH)$$

Equation 7-11

7.3.2.2. NITROGENOUS BIOCHEMICAL OXYGEN DEMAND

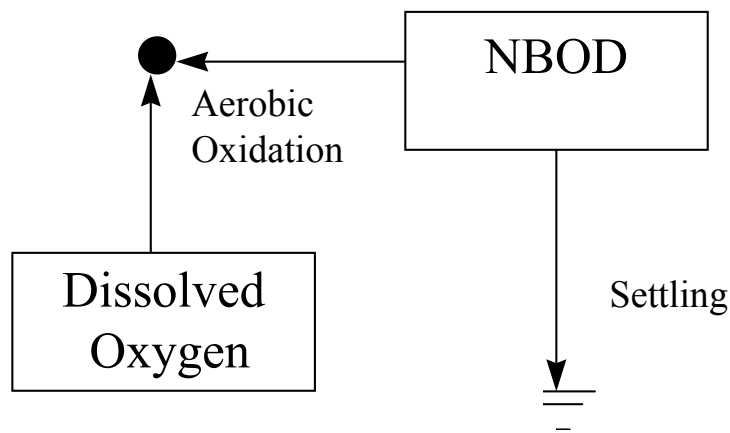


Figure 7-2

NBOD is a result of biochemical oxidation of organics by nitrogenous bacteria using oxygen as the terminal electron acceptor. The process involved has typically been predicted in mathematical models in two ways. The traditional way has been to use NBOD to represent, in a single stage, the transition of organic nitrogen to ammonia and then ammonia to nitrate with an associated consumption of oxygen. Alternatively, the process may also be predicted by simulating each of the forms of nitrogen separately (a two-stage process). The option of using both of these methods is included in EPD-RIV1. **However, to avoid “double-dipping” if NBOD is modeled, then nitrification is not considered as a sink for dissolved oxygen.** The basic reaction for NBOD is

$$\left(\begin{array}{c} \text{Rate of NBOD loss due to} \\ \text{oxidation and settling} \\ \text{g / m}^3 \text{ / day} \end{array} \right) = - \left(\text{KNBOD} + \frac{\text{SRNBOD}}{H} \right) * \text{NBOD}$$

Equation 7-12

where

KNBOD = temperature corrected rate coefficient for aerobic oxidation of NBOD, day⁻¹
 NBOD = concentration of NBOD, g O₂/m³, from previous time-step, C(14,l)
 CBODSR = rate coefficient for NBOD removal by settling, m/day
 H = depth, m

As with CBOD, the coefficient KNBOD is assumed to increase with DO according to a simple Monod function (cf. Hoover and Porges 1952.

$$\text{KNBOD} = \text{AKNBOD} * [\text{TH_NBOD}^{(\text{TEMP}-20.)}] * \left(\frac{\text{DO}}{\text{DO} + \text{DONBOD}} \right)$$

Equation 7-13

7.3.2.3.BIOCHEMICAL OXYGEN DEMAND: PARAMETERS AND CONSTANTS

Table 7-1. Parameters and Constants affecting Biochemical Oxygen Demand

1) Parameters that can appear in the Global Constants Cards			
Name	Explanation	Typical Value	Reference
TH_K1	Temperature coefficient for CBOD decay	1.047	OWR&S 1992
TH_BOD2	Temperature coefficient for CBOD2 decay	1.047	OWR&S 1992
TH_KDN	Temperature coefficient for denitrification of CBOD1	1.045	Bowie et al. 1985
TH_ADN2	Temperature coefficient for denitrification of CBOD2	1.047	
TH_NBOD	Temperature coefficient for NBOD decay	1.047	
2) Parameters that can appear in the Branch Constants Cards			
Name	Explanation	Typical Value	Reference
CBODSR	Settling rate for CBOD, m day ⁻¹	-0.36-0.36	Brown and Barnwell 1987
AND	Specific rate coefficient, uncorrected, for denitrification, day ⁻¹	0-1.0	Bowie et al. 1985
KOCB1	D.O. concentration at which CBOD decay rate is 1/2 maximum rate, mg/l		

KNCBDN	Nitrate conc. at which denitrification rate is $\frac{1}{2}$ maximum (CBOD types 1 and 2), mg/l		
FCBOD	Fraction of algal and macrophyte decay which goes to CBOD	0 to 1	
RBODSR	Settling rate for CBOD2 (m day ⁻¹)	-0.36-0.36	Brown and Barnwell 1987
ADN2	Specific rate coefficient, uncorrected, for denitrification for CBOD 2, day ⁻¹	0-1.0	Bowie et al. 1985
RBODDO	D.O. concentration at which CBOD2 decay rate is $\frac{1}{2}$ maximum rate, mg/l		
KOCBDN	D.O. concentration at which the rate of denitrification is reduced by $\frac{1}{2}$, mg/l	0.1	Bowie et al. 1985
FCRBOD	Fraction of algal and macrophyte decay which goes to CBOD2		
SRNBOD	Settling rate for NBOD (m day ⁻¹)		
DONBOD	D.O. concentration at which nitrogenous BOD decay rate is $\frac{1}{2}$ maximum rate, mg/l		

3) Parameters that vary by node

Name	Explanation	Typical Value	Reference
AK1	Rate coefficient for CBOD (day ⁻¹)	0.004-4	Bowie et al. 1985
KRBOD	Rate coefficient for CBOD 2 (day ⁻¹)	0.004-4	Bowie et al. 1985
AKNBOD	Rate coefficient for NBOD (day ⁻¹)	0-2	OWR&S 1992

7.3.3. Nitrogen Interactions

The forms of nitrogen (N) recognized by the model are organic nitrogen, ammonium, and nitrate. Nitrite is not considered because the overall rate of nitrification is ammonia-limited (Parker et al. 1975), and stream surveys do not exhibit significant increases in nitrite in nitrifying reaches (Garland 1978, Miller and Jennings 1979).

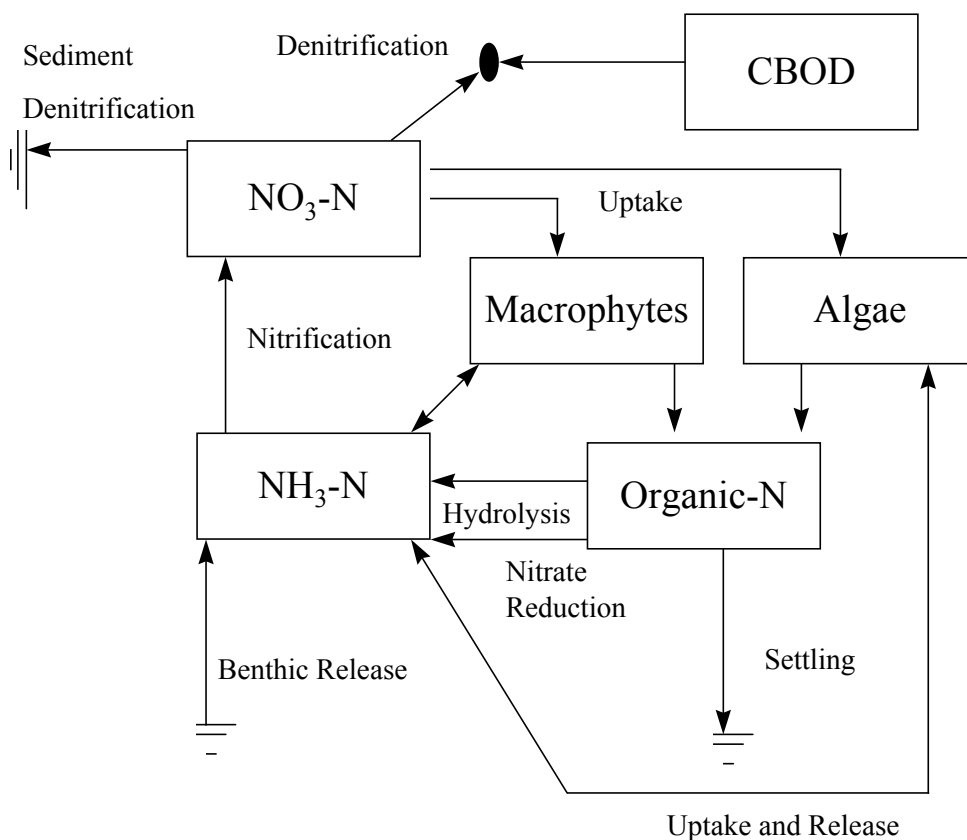


Figure 7-3

7.3.3.1. ORGANIC NITROGEN

Organic nitrogen is a constituent of the organic matter although its oxygen demand is not a part of the CBOD test result. In this model organic-N is produced from the decay of algae and macrophytes and lost due to hydrolysis and settling. For pure compounds, it is well known that their constituent nitrogen is released as ammonia during the exertion of the CBOD. However, in this model algae and macrophytes are assumed to release 100% organic nitrogen upon decay. This is done primarily to be consistent with other models (QUAL2E, Brown and Barnwell 1987). The rate loss is computed from

$$\left(\begin{array}{l} \text{Rate of loss of organic nitrogen} \\ \text{due to hydrolysis to ammonia} \\ \text{and settling} \\ \text{g - N / m}^3 \text{ / day} \end{array} \right) = \left(K1N + KDN + \frac{XONS}{H} \right) * ORGAN$$

Equation 7-14

where

- KIN = temperature and DO corrected rate coefficient for organic-N, day⁻¹ as computed from $K1N = ACK * TH_K1N(T-20.)*(1. + KOCB1)/DO$
 KDN = temperature corrected rate coefficient for nitrate reduction and anaerobic CBOD oxidation, day⁻¹
 KNSET = rate coefficient for removal of organic-N by settling, m/day
 H = stream depth, m
 ORGAN = concentration of organic-N, C(3,l), g-N/m³
 ACK = rate coefficient for organic-N hydrolysis to NH⁺₄, day⁻¹
 AKN = specific rate coefficient for organic-N decay, day⁻¹

The rate of organic-N increase resulting from algal and macrophyte decay is taken to be proportional to the rate of decay of algae and macrophytes. The nitrogen content of algae is variously reported as 7 to 10 percent by weight (Foree and McCarty 1968, Mackenthun and Ingram 1967), whereas the nitrogen content of macrophytes is only 2 to 4 percent by weight (Mackenthun and Ingram 1967, Gerloff 1969).

$$\left(\begin{array}{l} \text{Rate of increase of organic - N} \\ \text{due to algal / macrophyte decay} \\ \text{g - N / m}^3 \text{ / day} \end{array} \right) = + (ANCONT * ALGADK + MNCONT * MDEATH)$$

Equation 7-15

where

- ANCONT = nitrogen-to-biomass ratio in algae, g/g
 MNCONT = nitrogen-to-biomass ratio in macrophytes, g/g
 ALGADK = rate of algal decay, g/m³/day
 MDEATH = rate of macrophyte decay, g/m³/day

It may be noted that all of the algal/macrophyte N is assumed to be released upon decay of the cell. The algal/macrophyte decay rate itself is considered in greater detail in the following paragraphs. The net rate of change of the organic nitrogen concentration can be stated as:

$$\left(\begin{array}{c} \text{Net rate of accumulation} \\ \text{of organic nitrogen} \\ \text{g- N/ m}^3 \text{ / day} \end{array} \right) = - \left(\begin{array}{c} \text{loss due to} \\ \text{hydrolysis} \\ \text{and settling} \end{array} \right) + \left(\begin{array}{c} \text{gain due to} \\ \text{plant decay} \end{array} \right)$$

Equation 7-16

and stated in equation form as

$$\left(\begin{array}{c} \text{Net rate of accumulation} \\ \text{of organic nitrogen} \\ \text{g- N / m}^3 \text{ / day} \end{array} \right) = - \left(K1N + KDN + \frac{XONS}{H} \right) * ORGAN + [ANCONT*ALGADK + MNCONT*MDEATH]$$

Equation 7-17

7.3.3.2.AMMONIUM

Ammonium increases because of the hydrolysis of organic nitrogen (if it occurs). It decreases because of conversion of ammonium to nitrate (nitrification) and algal and macrophyte uptake. The rate of ammonium decrease because of nitrification is assumed to be first order

$$\left(\begin{array}{c} \text{Rate of nitrification} \\ \text{of ammonium- N to nitrate} \\ \text{g- N/ m}^3 \text{ / day} \end{array} \right) = -KN*NH_4^+ - N$$

Equation 7-18

where

KN = nitrification rate coefficient, day⁻¹
 NH₄⁺-N = ammonia-N concentration, g-N/m³

The rate coefficient KN is assumed to depend on oxygen and temperature in a way similar to K1

$$KN = AKN * [TH_KNH3^{(TEMP-20)}] * \left(\frac{DO}{DO + KON} \right)$$

Equation 7-19

where

AKN = uncorrected rate coefficient for nitrification, day⁻¹
 TH_KNH3 = temperature coefficient for ammonium oxidation (suggested value is 1.1)
 KON = Monod half-velocity constant for oxygen limitation of nitrification, g O₂/m³

EPD-RIV1 assumes that the plants can use both nitrate and ammonium. The total nitrogen consumption rate is partitioned between these two forms in proportion to their relative concentrations:

$$\left(\begin{array}{l} \text{Rate of ammonium - N} \\ \text{decrease due to} \\ \text{algal / macrophyte uptake} \\ \text{g - N / m}^3 \text{ / day} \end{array} \right) = - \left(\frac{NH_4^+ - N}{NH_4^+ - N + NO_3 - N} \right) * (ANCONT * ALGRO + MNCONT * MGRATE)$$

Equation 7-20

where

ANCONT = nitrogen-to-biomass ratio in algae,
 MNCONT = nitrogen-to-biomass ratio in macrophytes,
 NH₄⁺-N = concentration of ammonium nitrogen, g-N/m³, C(4,I)
 NO₃-N = concentration of nitrate nitrogen, g-N/m³, C(5,I)
 ALGRO = growth rate of algae, g/m³/day
 MGRATE = growth rate of macrophytes, g/m³/day

The partitioning function was introduced primarily to avoid double counting of nitrogen uptake by plants. Finally, a term for release of ammonium by the sediments is included:

$$\left(\begin{array}{l} \text{Benthic rate of} \\ \text{ammonium - N release by sediments} \\ \text{g - N / m}^3 \text{ / day, KBNNH3} \end{array} \right) = \frac{BENNH3}{H} TH_BENN^{(T-20)}$$

Equation 7-21

where

BENNH3 = benthic release rate, g-N/(m² day)
 TH_BENN = temperature coefficient for ammonia release
 H = depth, m
 T = temperature, °C

The ammonium-N reactions may be combined and stated as

$$\left(\begin{array}{c} \text{Net rate of} \\ \text{accumulation} \\ \text{of ammonium} \\ \text{g - N / m}^3 \text{ / day} \end{array} \right) = + \left(\begin{array}{c} \text{hydrolysis} \\ \text{of org - N} \end{array} \right) - \left(\begin{array}{c} \text{plant} \\ \text{uptake} \end{array} \right) - (\text{nitrification}) + \left(\begin{array}{c} \text{benthic} \\ \text{release} \\ \text{from} \\ \text{sediments} \end{array} \right)$$

Equation 7-22

and written in equation form as

$$\left(\begin{array}{c} \text{Net rate of} \\ \text{accumulation} \\ \text{of ammonium-N} \\ \text{g - N / m}^3 \text{ / day} \end{array} \right) = (K1N + KDN) * \text{ORGAN} - \\
 \text{ANCONT} * \left(1 - \frac{\text{NH}_4\text{N}}{\text{NH}_4^+ - \text{N} + \text{NO}_3^- - \text{N}} \right) \\
 * (\text{ALGRO} - \text{ALGADK}) - \text{MNCONT} * \left(1 - \frac{\text{NH}_4\text{N}}{\text{NH}_4^+ - \text{N} + \text{NO}_3^- - \text{N}} \right) \\
 * (\text{MGRATE} - \text{MDEATH}) + \text{KBNNH3} - \text{KN} * \text{NH}_4^+ - \text{N}$$

Equation 7-23

In Equation 7-23, the coefficient of the last term is K_S and the remaining terms make up SINKS of Equation 7-1.

7.3.3.3. NITRATE

Nitrate is formed by nitrification and removed by denitrification and plant uptake. Denitrification can take place in the water column under low DO conditions and in the bottom sediments. The accumulation of nitrate-N is stated as

$$\left(\begin{array}{c} \text{Net rate of} \\ \text{accumulation} \\ \text{of nitrate- N} \\ \text{g- N/ m}^3 \text{ / day} \end{array} \right) = - \left(\begin{array}{c} \text{water column} \\ \text{denitrification} \end{array} \right) + (\text{nitrification}) \\ - \left(\begin{array}{c} \text{plant} \\ \text{uptake} \end{array} \right) - \left(\begin{array}{c} \text{sediment} \\ \text{denitrification} \end{array} \right)$$

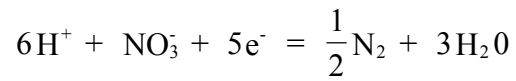
Equation 7-24

This can be written in equation form as

$$\left(\begin{array}{c} \text{Net rate of accumulation} \\ \text{of nitrate - N} \\ \text{g - N / m}^3 \text{ / day} \end{array} \right) = - \text{ONEQUI} * \text{KDN} * \text{CBOD} + \text{KN} * \text{NH}_4 \text{ N} \\ - (\text{ANCONT} * \text{ALGRO} + \text{MNCONT} * \text{MGRATE}) \\ * \left(\frac{\text{NO}_3^- \text{ - N}}{\text{NH}_4^+ \text{ - N} + \text{NO}_3^- \text{ - N}} \right) - (\text{KDNO2} * \text{NO}_3^- \text{ - N})$$

Equation 7-25

All terms in Equation 7-25 are in the SINKS term of Equation 7-1 and K_S is KDNO2, where KDSed is the sediment denitrification rate. The coefficient ONEQUI (suggested value 0.35) is a conversion factor for oxygen to nitrogen equivalents and is evaluated as follows. The half cell reaction for nitrate reduction is



Equation 7-26

Therefore, the equivalent weight of nitrate nitrogen is 2.8 g. The equivalent weight of oxygen is 8.0 g, and the mass of nitrogen equivalent to 1 g of oxygen is 0.35 g.

7.3.3.4. INPUT COEFFICIENTS FOR NITROGEN

Table 7-2. Parameters and Constants affecting Nitrogen

1) Parameters that can appear in the Global Constants Cards			
Name	Explanation	Typical Value	Reference
TH_K1N	Temperature coefficient for organic nitrogen decay	1.047	Brown and Barnwell 1987
TH_KNH3	Temperature coefficient for nitrification	1.085	OWR&S 1992
TH_KDNO2	Temperature coefficient for sediment denitrification		
TH_BENN	Temperature coefficient for benthic release of ammonia	1.074	Brown and Barnwell 1987
ANCONT	Nitrogen-to-biomass ratio in algae	0.075 (0.07-0.1)	Environmental Laboratory 1995
MNCONT	Nitrogen-to-biomass ratio in macrophytes	0.02-0.4	Environmental Laboratory 1995
2) Parameters that can appear in the Branch Constants Cards			
Name	Explanation	Typical Value	Reference
KON	DO concentration at which nitrification rate is 1/2 (mg/l)		
ACK	Rate coefficient for organic-N decay to NH ₃ , day ⁻¹	0.02-0.4	Brown and Barnwell 1987
XONS	Settling rate for Organic N, m day ⁻¹	0.001-0.1	Brown and Barnwell 1987
AKN	Specific rate coefficient, uncorrected, for nitrification, day ⁻¹	0.025-6	Bowie et al. 1985
KDN02	Sediment denitrification rate, day ⁻¹		
3) Parameters that vary by node			
Name	Explanation	Typical Value	Reference
BENNH3	Rate coefficient for sediment ammonia release, g m ⁻² day ⁻¹	Variable	

7.3.4. Phosphorus Interactions

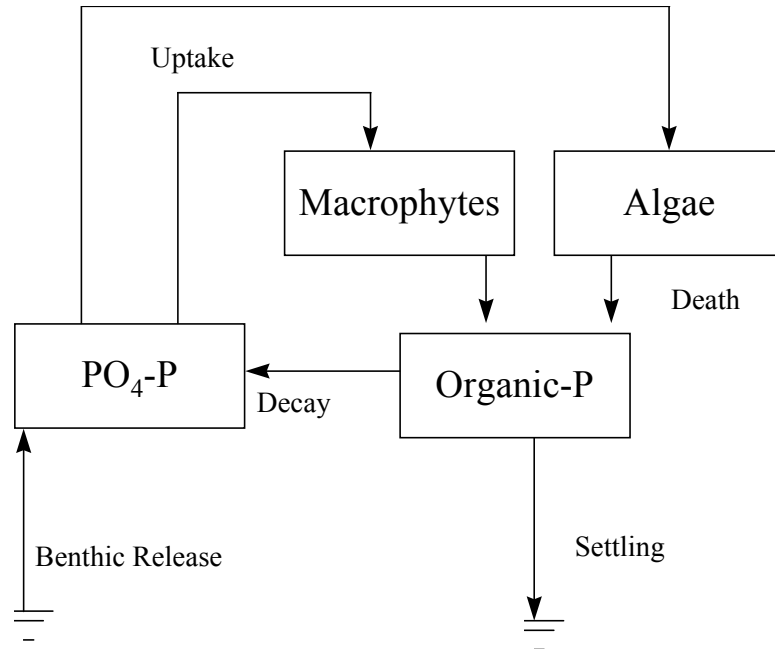


Figure 7-4

7.3.4.1. ORGANIC PHOSPHORUS

Organic P can be lost through settling and gained through plant decay. The algal/macrophyte sources and sinks of P are by:

$$\left(\begin{array}{l} \text{Release of org-P by} \\ \text{algal/ macrophyte decay} \\ \text{g-P/ m}^3 \text{ / day} \end{array} \right) = \text{APCONT} * \text{ALGADK} + \text{MPCONT} * \text{MDEATH}$$

Equation 7-27

where

APCONT = phosphorus-to-biomass ratio in algae,
 MPCONT = phosphorus-to-biomass ratio in macrophytes,
 ALGADK = death rate of algae, $\text{g/m}^3/\text{day}$
 MDEATH = death rate of macrophytes, $\text{g/m}^3/\text{day}$

The loss of organic P due to hydrolysis and settling is stated as

$$\left(\begin{array}{c} \text{Loss of org-P due to} \\ \text{hydrolysis to phosphate} \\ \text{and settling} \\ \text{g-P / m}^3 \text{ / day} \end{array} \right) = (\text{ORG-P}) * \left(\text{KPDK} + \frac{\text{KPSET}}{H} \right)$$

Equation 7-28

where

ORG-P = organic-P concentration, C(6,I), g/m³
 KPDK = organic-P hydrolysis rate, day⁻¹
 KPSET = organic-P settling rate, m/day
 H = depth, m

The net rate of accumulation of organic-P is stated as

$$\left(\begin{array}{c} \text{Net rate of accumulation} \\ \text{of org-P} \\ \text{g / m}^3 \text{ / day} \end{array} \right) = - \left(\begin{array}{c} \text{hydrolysis to phosphate} \\ \text{and settling} \\ \text{g / m}^3 \text{ / day} \end{array} \right) + (\text{plant decay})$$

Equation 7-29

or

$$\left(\begin{array}{c} \text{Net rate of accumulation of} \\ \text{org-P per unit volume,} \\ \text{g P / m}^3 \text{ / day} \end{array} \right) = - \text{ORG-P} * \left(\text{KPDK} + \frac{\text{KPSET}}{H} \right) + (\text{MPCONT} * \text{MDEATH} + \text{APCONT} * \text{ALGADK})$$

Equation 7-30

7.3.4.2.PHOSPHATE-P

Phosphate-P is taken up by plants, produced by the hydrolysis of organic-P, and released from sediments. The uptake by plants is described by:

$$\left(\begin{array}{l} \text{Uptake of phosphate - P by} \\ \text{algal / macrophyte growth} \\ \text{g - P / m}^3 \text{ / day} \end{array} \right) = - \text{APCONT} * \text{ALGRO} - \text{MPCONT} * \text{MGRATE}$$

Equation 7-31

where

APCONT = phosphorus-to-biomass ratio in algae,
 MPCONT = Phosphorus-to-biomass ratio in macrophytes,
 ALGRO = growth rate of algae, g/m³/day
 MGRATE = growth rate of macrophytes, g/m³/day

A term for release of phosphate by the sediments is included:

$$\left(\begin{array}{l} \text{Benthic rate of} \\ \text{Phosphate - P release by sediments} \\ \text{g - P / m}^3 \text{ / day, KBENPO4} \\ \text{and lost due to decay} \end{array} \right) = \frac{\text{BENPO4}}{\text{H}} \text{TH_BENPO4}^{(T-20)} - \text{APO4 TH_SORP}^{(TEMP-20.)} \text{OPO4}$$

Equation 7-32

where

BENPO4 = benthic release rate, g-P/(m² day)
 TH_BENPO4 = temperature coefficient for phosphate release
 TH-SORP = temperature coefficient for phosphate sorption or loss
 APO4 = phosphate loss rate (1/day)
 OPO4 = phosphate concentration (mg/l)
 H = depth, m
 TEMP = temperature, °C

The net rate of accumulation of phosphate-P is stated as

$$\left(\begin{array}{l} \text{Net rate of accumulation} \\ \text{of phosphate - P} \\ \text{g - P / m}^3 \text{ / day} \end{array} \right) = \left(\begin{array}{l} \text{hydrolysis of} \\ \text{organic - P} \end{array} \right) + \left(\begin{array}{l} \text{sediment} \\ \text{release} \end{array} \right) - (\text{loss}) - \left(\begin{array}{l} \text{uptake by} \\ \text{algae / macrophytes} \end{array} \right)$$

Equation 7-33

or

$$\left(\begin{array}{l} \text{Net rate of accumulation} \\ \text{of phosphate - P} \\ \text{g - P / m}^3 \text{ / day} \end{array} \right) = + \text{ORG - P} * \text{KPKDK} + \text{KBENPO4} - (\text{APCONT} * \text{ALGRO} + \text{MPCONT} * \text{MGRATE}) - \text{APO4} * \text{TH_SORP}^{(\text{TEMP}-20)} * \text{OPO4}$$

Equation 7-34

7.3.4.3. PARAMETERS AND COEFFICIENTS FOR PHOSPHORUS

Table 7-3. Parameters and Constants affecting Phosphorus

1) Parameters that can appear in the Global Constants Cards			
Name	Explanation	Typical Value	Reference
TH_SORP	Temperature coefficient for phosphate adsorption		
TH_BENP	Temperature coefficient for benthic release of phosphorus	1.074	Brown and Barnwell 1987
APCONT	Phosphorus to biomass ratio in algae	0.01	Environmental Laboratory 1995
MPCONT	Phosphorus to biomass ratio in macrophytes		
2) Parameters that can appear in the Branch Constants Cards			
Name	Explanation	Typical Value	Reference
KPDK	Decay rate for organic -P, day ⁻¹	0.01-0.7	Brown and Barnwell 1987
KPSET	Settling rate for organic-P, m day ⁻¹	0.001-0.1	Brown and Barnwell 1987
APO4	Specific rate coefficient, uncorrected, for phosphate adsorption, day ⁻¹		
3) Parameters that vary by node			
Name	Explanation		Reference
BENPO4	Rate coefficient for sediment phosphorus release, g m ⁻² day ⁻¹	Variable	

7.3.5. Algae

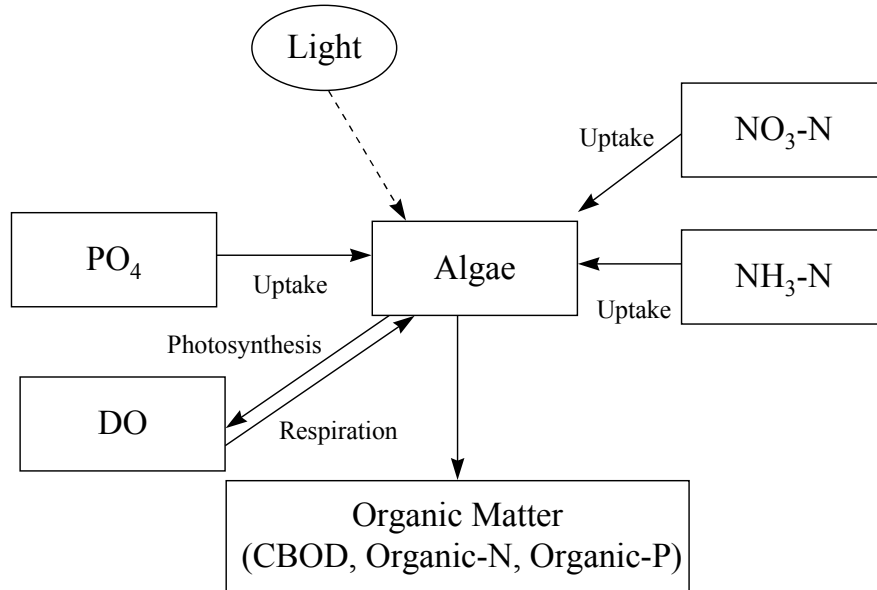


Figure 7-5

Algae are modeled as a state variable while macrophytes are not. Predicted algal biomass is dependent upon transport, growth and death (respiration). The rate of growth is computed from a maximum temperature corrected rate which is reduced by the effects of light and nutrients.

7.3.5.1. ALGAL GROWTH

The rate of algal growth is affected by light intensity, self-shading, and nutrients (N and P). The effect of light intensity on the algal growth rate is obtained by substituting Beer's law into a Monod-type relationship and integrating over the depth of the channel cross section. The effects of nitrogen and phosphorus on growth are accounted for using Monod-type expressions, similar to those in QUAL2E (Brown and Barnwell 1987). This results in a multiplicative expression for growth also similar to one of the QUAL2E growth options. The resulting growth rate in reach I is then

$$\text{ALGRO} = \text{C}(12, \text{I}) * \text{KALGRO} * \left(\frac{1}{\text{KEXT} * \text{H}} \right) * \ln \left(\frac{\text{KLITE} + \text{SWALG}}{\text{KLITE} + \text{SWALG} * \text{EXP}(-\text{KEXT} * \text{H})} \right) * \text{FN} * \text{FP}$$

Equation 7-35

or

$$\text{ALGRO} = \text{C}(12, \text{I}) * \text{ALG1} * \text{FL} * \text{FN} * \text{FP}$$

Equation 7-36

where

- ALGRO = algal growth rate, corrected for light, temperature, and nutrient availability, g-biomass/m³ day⁻¹
 C(12,I) = algal concentration at node I at time t (g-biomass/m³)
 KALGRO = maximum specific algal growth rate, day⁻¹. Input as KALGRO, renamed ALG1 in subroutine SEG
 KEXT = light extinction coefficient, m⁻¹, corrected for algal self-shading
 H = hydraulic depth, A/B, m
 KLITE = half-velocity constant for light intensity, watt/m²
 SWALG = short-wave radiation intensity at the water surface, watt/m²
 FN = nitrogen growth adjustment factor
 FP = phosphorus growth adjustment factor
 FL = light growth adjustment factor

The light extinction coefficient KEXT is coupled to algal density using the nonlinear equation

$$\text{KEXT}(\lambda) = \lambda_0 + \lambda_1 [\alpha_0 * \text{C}(12, \text{I})] = \lambda_2 [\alpha_0 * \text{C}(12, \text{I})]^{2/3}$$

Equation 7-37

where

- λ = KEXT = corrected extinction coefficient
 λ_0 = nonalgal portion of light extinction coefficient - user specified (LAMBDA0)
 λ_1 = linear algal self-shading - user specified (LAMBDA1) value previously used, 0.0088 m⁻¹ (μg Chl a/L)⁻¹ (Riley equation in Bowie et al. 1985)
 λ_2 = nonlinear algal self-shading - user specified (LAMBDA2) value previously used, 0.054 m⁻¹ (μg-Chl a/L)^{-2/3} (Riley equation in Bowie et al. 1985)

α_0 = algae chlorophyll conversion factor - user specified (ALPHA0)
 $C(12,l)$ = algal biomass concentration at node l

The same modification of KEXT is also used to modulate the growth rate of macrophytes.

To account for diel effects, the surface light intensity (net short wave radiation) is computed as a function of the time of day. This is accomplished in subroutine HEATFLUX if the direct heat balance option is used; otherwise, the following relation is used

where

$$SWALG = HNEFSW * \sin \left[\frac{\pi * (CLOCK - DAWN)}{LAMBDA} \right]$$

Equation 7-38

where

HNEFSW = maximum surface light intensity at local noon, watts/m²
 π = 3.14159
 CLOCK = actual time of day, 24-hr clock
 DAWN = time of local dawn, 24-hr clock
 LAMBDA = elapsed time between local dawn and local sunset, hr

Algal growth is modulated by nutrient (N and P) availability using a Monod-like expression identical to that used by QUAL2E. The following equations are used

$$FN = \frac{NPOOL}{(NPOOL + KNPOOL)}$$

Equation 7-39

$$FP = \frac{PO_4}{(PO_4 + KPO4X)}$$

Equation 7-40

where

FN = nitrogen limitation factor
 FP = phosphate limitation factor
 NPOOL = (nitrate+ammonia) concentration, g/m³
 KNPOOL = half-velocity constant relating inorganic nitrogen to algal growth, g/m³
 PO₄ = phosphate concentration, g/m³
 KPO4X = half-velocity constant relating phosphate concentration to algal growth rate, g/m³

7.3.5.2. ALGAL DECAY

Algal respiration and death (i.e., decay) occur continuously and can be described as follows

$$\left(\begin{array}{c} \text{Corrected} \\ \text{algal} \\ \text{decay rate} \\ \text{(ALGADK)} \end{array} \right) = \left(\begin{array}{c} \text{algal} \\ \text{concentration} \end{array} \right) * \left(\begin{array}{c} \text{specific algal} \\ \text{decay rate} \\ \text{(ALGO)} \end{array} \right) * \left(\begin{array}{c} \text{DO/ decay} \\ \text{correction} \end{array} \right)$$

Equation 7-41

In equation form, decay becomes

$$\text{ALGADK} = \text{C(12,I)} * \text{KALGDK} * \left(\frac{\text{DO}}{\text{DO} + \text{KOALDK}} \right)$$

Equation 7-42

where

ALGADK = algal decay rate, g/(m³day)
 KALGDK = maximum specific algal decay rate, day⁻¹
 C(12,I) = algae concentration at node i, g/m³
 KOALDK = DO half-velocity constant for algal decay, g/m³

7.3.5.3. PARAMETERS AND CONSTANTS AFFECTING ALGAE

Table 7-4. Parameters and Constants affecting Algae

1) Parameters that can appear in the Global Constants Cards			
Name	Explanation	Typical Value	Reference
TH_AGRO	Temperature coefficient for algal growth	1.047	Brown and Barnwell 1987
TH_ADIE	Temperature coefficient for algal death	1.047	Brown and Barnwell 1987

DAWN	Time of sun rise (hours)	-	
SUNSET	Time of sun set (hours)	-	
2) Parameters that can appear in the Branch Constants Cards			
Name	Explanation	Typical Value	Reference
KALGRO	Algal growth rate, day ⁻¹	1-3	Brown and Barnwell 1987
KNPOOL	Total nitrogen concentration at which algal growth rate is reduced by 1/2, mg/l	0.01-0.3	Brown and Barnwell 1987
KPO4X	Phosphorous concentration at which algal growth rate reduced by 1/2, mg/l	0.001-0.05	Brown and Barnwell 1987
KLITE	Light intensity at which photosynthesis rate reduced by 1/2 (W m ⁻²)	1.2-6	Brown and Barnwell 1987
HNEFSW	Surface light intensity at local noon (W m ⁻²)	Variable	
LAMBDA0	Non-algal portion of light extinction coefficient (m ⁻¹)		
LAMBDA1	Linear algal self shading coefficient (m ⁻¹ (μg - Chl-1/l) ⁻¹)	0.0088	Environmental Laboratory 1995
LAMBDA2	Nonlinear algal self shading coefficient (m ⁻¹ (μg - Chl-1/l) ^{-2/3})	0.054	Environmental Laboratory 1995
ALPHA0	Conversion factor from algae biomass to chlorophyll-a	10-100	Brown and Barnwell 1987
KALGDK	Algal decay rate, day ⁻¹	0.05-0.5	Brown and Barnwell 1987
KOALDK	D.O. concentration at which algal decay rate is 1/2 maximum, mg/l		
3) Parameters that vary by node			
Name	Explanation	Typical Value	Reference
NONE			

7.3.6. Macrophytes

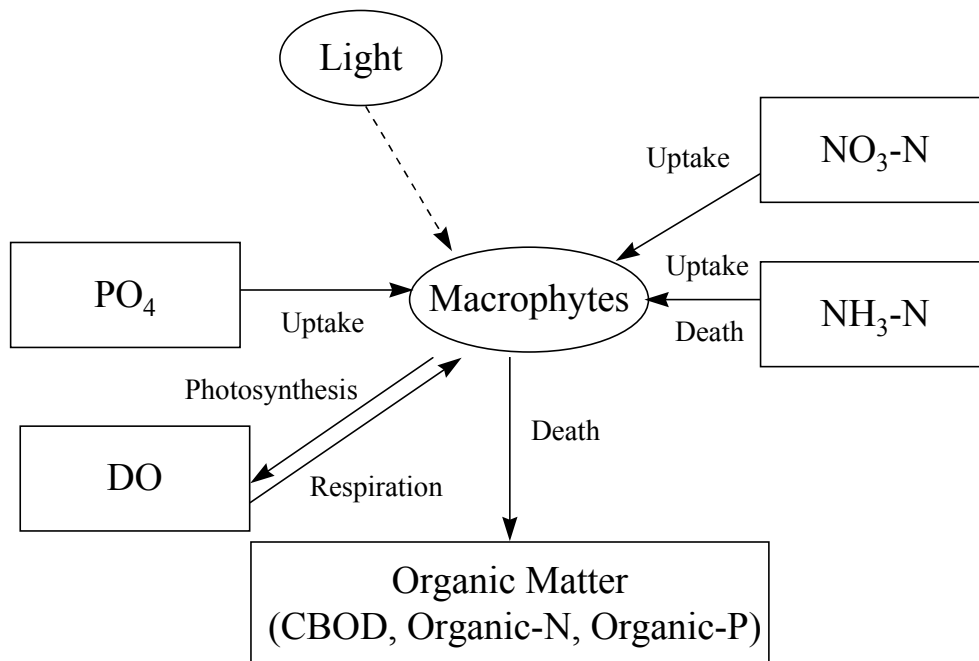


Figure 7-6

While algae are modeled as a state variable, macrophytes are not. Macrophytes are assumed to be benthal.

7.3.6.1. MACROPHYTE GROWTH

The macrophyte growth rate, MGRATE ($\text{g/m}^3/\text{day}$), is taken to be the product of the benthal macrophyte density, the local light intensity (corrected for attenuation en route), and a reaction rate coefficient. To further simplify the analysis, the stream cross section is approximated as a rectangle. Thus, the plant growth is distributed along the channel bottom and sides.

$$\left(\begin{array}{c} \text{Plant growth per} \\ \text{unit length of channel} \\ \text{(MGRATE)} \\ \text{g/ m}^3 \text{/ d} \end{array} \right) = \left(\begin{array}{c} \text{bottom} \\ \text{growth} \end{array} \right) + \left(\begin{array}{c} \text{side} \\ \text{growth} \\ 2 \text{ sides} \end{array} \right)$$

Equation 7-43

or

$$\text{MGRATE} = \frac{B * \text{MACRO} * \text{SWALG} * e^{(-\text{KEXT} * H)}}{A} + \left(\frac{2}{\text{KEXT} * A} \right) * \text{MACRO} * \text{SWALG} * [1. - e^{(-\text{KEXT} * H)}]$$

Equation 7-44

where

- B = stream top width, m
 MACRO = MACGRO (m²/watt/day) * MACROB (g/m²), (g/watt*day)
 MACLITE = macrophyte growth rate coefficient, m²/watt/day
 MACROB = macrophyte surface density, g/m²
 SWALG = light intensity (net short-wave radiation) at the water surface, watt/m²
 KEXT = light extinction coefficient for the particular reach, m⁻¹
 H = hydraulic depth, m
 A = channel cross-sectional area, m²

SWALG must appear explicitly in the equation because it is recomputed at each time-step. The first term on the right-hand side of Equation 7-44 includes the light intensity on the bottom (SWALG*EXP(-KEXT*H)). The second term is the summation of the plant growth occurring at all depths on both (vertical) sides:

$$\text{MGRATE}_{\text{sides}} = \frac{2 * \text{MACRO} * \text{SWALG} * \int_0^H \text{EXP}[-\text{KEXT}(H-Z)] * dZ}{A}$$

$$\left(\frac{\text{g}}{\text{m}^3 * \text{day}} \right)$$

Equation 7-45

where

MACRO = MACLITE*MACROB

In one instance, numerical problems are presented by the expression

$$\frac{2}{KEXT} * (1 - e^{(-KEXT * H)}) + B * e^{(-KEXT * H)}$$

Equation 7-46

used in determining available photosynthetic energy and must be handled. First, the number of calls to the external function EXP (exponentiation) can be halved by rewriting the above expression as the algebraically equivalent

$$\frac{2}{KEXT} + \left(B - \frac{2}{KEXT} \right) * e^{(-KEXT * H)}$$

Equation 7-47

The above expression, however, becomes numerically unstable as KEXT approaches zero, although mathematically it approaches the value

$$2 * H + B$$

Equation 7-48

This problem is handled by taking a Taylor's series expansion of EXP(-KEXT*H) in the expression $2./KEXT*[1.-EXP(-KEXT*H)]$ about KEXT = 0 carried to three terms,

$$\frac{2}{KEXT} * [1. - (1. - KEXT * H + \frac{(KEXT * H)^2}{2} =)]$$

Equation 7-49

This simplifies to

$$H * (2. - KEXT * H)$$

Equation 7-50

Equation 7-47 is then expressed as

$$H * (2. - KEXT * H) + B * e^{(-KEXT * H)}$$

Equation 7-51

for KEXT less than 0.01.

Therefore, for KEXT less than 0.01

$$MGRATE = MACROB * MACGRO * TH_MGRO^{(TEMP-20.)}$$

$$SWALG * \frac{[H (2 - KEXT * H) B e^{-KEXT * H}]}{A(I)}$$

Equation 7-52

For $KEXT \geq 0.01$

$$MGRATE = MACROB * MACGRO * TH_MGRO^{(TEMP-20.)}$$

$$SWALG * \frac{\left[\frac{2}{KEXT} + \left((B(I) - \frac{2}{KEXT}) e^{-KEXT * H} \right) \right]}{A(I)}$$

Equation 7-53

Note that since macrophytes obtain their nutrients from the sediments (Bole and Allan 1978, Carignan and Kalff 1980), stream nutrient levels are not considered in computing their growth rates.

7.3.6.2. MACROPHYTE DECAY

Macrophytes are presumed to respire and die (i.e. decay) continuously. The decay rate is controlled, in part by the DO level since decay slows at low DO levels. Because of the lack of reasonably precise data, no temperature correction is attempted. The decay rate is represented as

$$MDEATH = MACROB * MACDKY * TH_MDIE^{(TEMP-20.)}$$

$$(B(I) + 2H) * A(I) * \frac{DOX}{1. + KOALDK}$$

Equation 7-54

where

MDEATH = macrophyte decay rate, g/m³/d
 MACDKY = macrophyte specific decay rate, day⁻¹
 MACROB = macrophyte density, g/m²
 KOALDK = Monod half-velocity constant for oxygen limitation of macrophyte decay, g O₂/m³
 DOX = average dissolved oxygen concentration, g/m³
 H = depth, m
 B = width, m
 A = cross-sectional area, m²

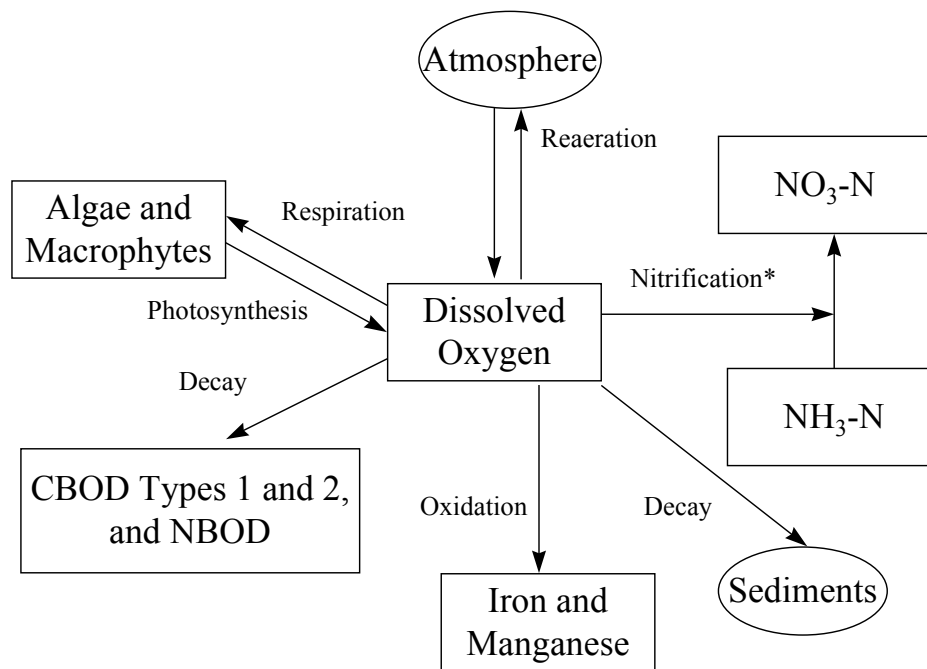
7.3.6.3. PARAMETERS AND PROCESSES AFFECTING ALGAE

Table 7-5. Parameters and Constants affecting Macrophytes

1) Parameters that can appear in the Global Constants Cards			
Name	Explanation	Typical Value	Reference
TH_MGRO	Temperature coefficient for macrophyte growth		
TH_MDIE	Temperature coefficient for macrophyte death		
DAWN	Time of sun rise (hours)	-	
SUNSET	Time of sun set (hours)	-	
2) Parameters that can appear in the Branch Constants Cards			
Name	Explanation	Typical Value	Reference
KLITE	Light intensity at which photosynthesis rate reduced by ½ (W m ⁻²)	1.2-6	Brown and Barnwell 1987

HNEFSW	Surface light intensity at local noon (W m^{-2})	Variable	
3) Parameters that vary by node			
Name	Explanation	Typical Value	Reference
MACROB	Macrophyte Density on Channel Surfaces, g m^{-2}		
MACGRO	Specific macrophyte Growth Rate, $\text{m}^2 \text{W}^{-1} \text{day}^{-1}$		
MACDKY	Specific macrophyte Decay Rate, day^{-1}		

7.3.7. Dissolved Oxygen



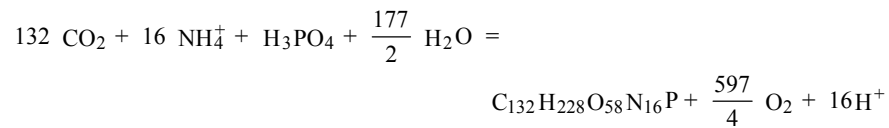
* Only if NBOD is not simulated

Figure 7-7

The sources of dissolved oxygen (O_2) are reaeration and photosynthesis; the sinks are the exertion of CBOD, nitrification, plant respiration, and the oxidation of reduced iron and manganese.

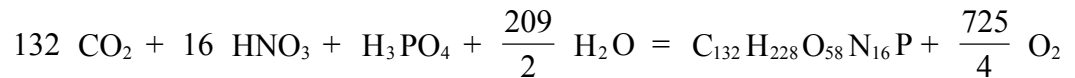
7.3.7.1. ALGAL AND MACROPHYTE PHOTOSYNTHESIS AND RESPIRATION

The present model uses equations developed for algal synthesis and decay for both algae and macrophytes. The stoichiometry of these processes can be illustrated using the data of Foree and McCarty (1968) and depends on whether ammonium or nitrate is involved. The stoichiometric coefficients are user input and may be estimated from the following equations



Equation 7-55

and



Equation 7-56

The oxygen production indicated by Equation 7-55 when ammonium is the nitrogen source is 1.59 g O₂/g algae, and from Equation 7-56 is 1.94 g O₂/g algae when nitrate is the nitrogen source. Therefore, the rate of oxygen production by photosynthesis depends upon the relative proportions of ammonia and nitrate consumed:

$$\left(\begin{array}{l} \text{Rate of oxygen} \\ \text{production by} \\ \text{photosynthesis} \\ \text{g O}_2 / \text{m}^3 / \text{day} \end{array} \right) = \left[+ \text{OPDECY} + \text{ONEQUI} * \left(\frac{\text{NO}_3^- - \text{N}}{(\text{NO}_3^- - \text{N} + \text{NH}_3 - \text{N})} \right) \right] \\ * (\text{ALGRO} + \text{MGRATE})$$

Equation 7-57

where recommended values are

$$\text{OPDECY} = 1.59$$

$$\text{ONEQUI} = 0.35$$

The rate of oxygen consumption resulting from algal decay does not involve nitrification, so it is the reverse of Equation 7-55 after accounting for the fraction that feeds directly into CBOD:

$$\left(\begin{array}{c} \text{Rate of oxygen consumption} \\ \text{by plant decay} \\ \text{g O}_2 / \text{m}^3 / \text{day} \end{array} \right) = \text{OPDECY} * (\text{ALGADK} + \text{MDEATH})$$

Equation 7-58

The rate of oxygen consumption resulting from CBOD decay is equal to the rate of CBOD decay, because of the definition of CBOD. The rate of oxygen consumption resulting from ammonium oxidation is based on the computed nitrification rate and a stoichiometric coefficient, which may be estimated from



Equation 7-59

The oxygen consumption here is ONITRI g O₂/g N (ONITRI = 4.57). Some authors prefer a value of 4.33 g O₂/g N, arguing that some of the ammonium consumed by the nitrifiers goes into cell synthesis (Garland 1978). However, the nitrifiers are themselves subject to predation, which returns the incorporated ammonia to the stream for further nitrification. The actual amount of ammonia removed or nitrified is unknown, but the difference between 4.57 and 4.33 is insignificant when one considers the usual accuracy of field data.

7.3.7.2. REAERATION

The rate of oxygen uptake resulting from stream reaeration can be formulated as:

$$\left(\begin{array}{l} \text{Increase in DO} \\ \text{due to reaeration} \\ \text{g O}_2 / \text{m}^3 / \text{day} \end{array} \right) = K_2 * (\text{DOSAT} - \text{DO})$$

Equation 7-60

where

K_2 = reaeration rate coefficient, day^{-1}
 DOSAT = local solubility of oxygen, $\text{g O}_2/\text{m}^3$
 DO = local oxygen concentration, $\text{g O}_2/\text{m}^3$

Therefore, the rate of reaeration depends upon the gradient between the predicted (local) and saturation dissolved oxygen concentrations and upon the computed reaeration rate coefficient.

There are two equations the user may select for computing the local solubility of oxygen:

- The Elmore and Hayes (1960) formulation, or
- The APHA (1985) formulation

The Elmore and Hayes (1960) formulation is

$$\text{DOSAT} = 14.652 + [-0.41022 + (0.007991 - 0.000077774 * \text{TEMP}) * \text{TEMP}]$$

Equation 7-61

and the APHA (1985) expression is given by

$$\text{DOSAT} = -139.34411 + \frac{1.575701\text{E}05}{\text{TK}} - \frac{6.642308\text{E}07}{\text{TK}^2} + \frac{1.243800\text{E}10}{\text{TK}^3} - \frac{8.621949\text{E}11}{\text{TK}^4}$$

Equation 7-62

where

TEMP = water temperature, °C
 TK = water temperature, °K or TEMP + 273.

The user may also elect to have the dissolved oxygen saturation concentration adjusted for altitude by (APHA 1985)

$$\text{DOSAT} = \text{DOSAT} * (1 - 0.00000697 * \text{ELEV0})^{5.167}$$

Equation 7-63

where

ELEV0 = reference elevation of the waterbody, ft

The reaeration rate coefficient is computed for both stream and wind reaeration and the larger of the two values used.

7.3.7.2.1.Stream Reaeration

There are several options available in EPD-RIV1 for computing stream reaeration. **The method used for computing stream reaeration is determined by the coefficients input by the user.** The options include:

- 1) A user specified value,
- 2) Compute coefficient using user specified coefficients and a general formulation,
- 3) Compute using Tsivoglou's formulation,
- 4) Compute using COVAR's method,
- 5) Set the rate of reaeration equal to zero.

The order of the options listed above also represents their hierarchy in the model. That is, an option selected near the top of the list will override one near the bottom. For example, if the user selects Covar's method but specifies a rate of reaeration for a particular node, the specified rate will be used. Also the rate will be set to zero only if none of the other options are specified. That means, for example, if the users wishes to set reaeration equal to zero they must either specify a very low number for the first option or none of the parameters that would cause the computation of the rate.

1) Where the user specifies the rate of reaeration, the rate used by the model is

$$K2 = KREAER / H$$

Equation 7-64

where

K2 = reaeration rate, 1/day
 KREAR = the user specified rate at node (I), m/day
 H = the hydraulic depth (Area/Top Width), m

Note that this rate is not temperature corrected.

2) For use of the general formulation,

$$K2 = \frac{AG * (U^{E1})}{(H^{E2})} * [TH_K2^{(TEMP-20.)}]$$

Equation 7-65

where

K2 = reaeration rate, 1/day
 AG, E1, E2 = empirical coefficients
 TH_K2 = temperature correction coefficient for reaeration
 H = the hydraulic depth (Area/Top Width), m

In using Equation 7-65, it must be noted that AG is sometimes given for 25 °C.

3) For those who prefer the Tsivoglou-Wallace (1972) equation in its published form, provision has been made in the program to permit its use as an option where:

$$K2 = \frac{TSIV * [E(I-1) - E(I)]}{(DX / U)} * TH_K2^{(TEMP-20)}$$

Equation 7-66

where

K2 = reaeration rate, 1/day
 TSIV = empirical coefficient, m⁻¹ (the value is entered in units of ft⁻¹ and converted, suggested value is 0.054)
 E(I-1), E(I) = water surface elevations at the upstream and downstream ends of the reach under consideration, m
 DX = length of the reach, m
 U = reach stream velocity, m/day
 TH_K2 = temperature correction coefficient for reaeration

In using Equation 7-66, it must be noted that TSIV is sometimes given for 25 °C.

4) Covar's Method

EPD-RIV1 can also calculate stream reaeration based on the Covar method (Covar, 1976). This method calculates reaeration as a function of velocity and depth by one of three formulas -- Owens, Churchill, or O'Connor- Dobbins, respectively:

$$K2 = 5.349 U^{0.67} H^{-1.85}$$

Equation 7-67

$$K2 = 5.049 U^{0.97} H^{-1.67}$$

Equation 7-68

or

$$K2 = 3.93 U^{0.5} H^{-1.5}$$

Equation 7-69

where:

K2 = flow-induced reaeration rate coefficient at 20°C, 1/day
 U = average water velocity, m/sec
 H = hydraulic depth, m

The Owens formula is automatically selected for segments with depth less than 2 feet. For segments deeper than 2 feet, the O'Connor-Dobbins or Churchill formula is selected based on a consideration of depth and velocity. Deeper, slowly moving rivers require O'Connor-Dobbins; moderately shallow, faster moving streams require Churchill. Segment temperatures are used to adjust the flow-induced K2(20 °C) by the standard formula:

$$K2(T) = K2(20^{\circ}\text{C}) TH_K2^{(T-20)}$$

Equation 7-70

where:

T = water temperature, °C
 K2(T) = reaeration rate coefficient at ambient temperature, 1/day
 TH_K2 = temperature coefficient, unitless

5) No reaeration. If the user does not specify a reaeration rate or the coefficients in the general or Tsivoglou-Wallace (1972) formulation, or select Covar's method, then the coefficient (K2) for stream reaeration will be set to zero. The only other way by which the user can effectively eliminate stream reaeration is to set the user specified rate (KREAR) to a very small (but non-zero) number.

7.3.7.2.2.Wind-Driven Reaeration

Wind-induced reaeration is determined by O'Connor (1983). This method calculates reaeration as a function of wind speed, air and water temperature, and depth using one of three formulas:

$$KW = \frac{86400}{100 H} \left(\frac{D_{OW}}{v_W} \right)^{2/3} \left(\frac{\rho_a}{\rho_W} \right)^{1/2} \frac{k^{1/3}}{\Gamma} \sqrt{C_d} (100 \bullet W)$$

Equation 7-71

or

$$KW = \frac{86400}{100 H} \left[(TERM1 \bullet 100W)^{-1} + (TERM2 \sqrt{100W})^{-1} \right]^{-1}$$

where

$$TERM1 = \left(\frac{D_{OW}}{v_W} \right)^{2/3} \left(\frac{\rho_a}{\rho_W} \right)^{1/2} \frac{k^{1/3}}{\Gamma_u} \sqrt{C_d}$$

$$TERM2 = \left(\frac{D_{OW}}{k z_0} \frac{\rho_a v_a}{\rho_W v_W} \sqrt{C_d} \right)^{1/2}$$

Equation 7-72

or

$$KW = \frac{86400}{100 H} \left(\frac{D_{OW}}{k z_e} \frac{\rho_a v_a}{\rho_W v_W} \sqrt{C_d} \right)^{1/2} \sqrt{100W}$$

Equation 7-73

where:

KW = wind-induced reaeration rate coefficient, day⁻¹
H = the hydraulic depth (Area/Top Width), m

W	= time-varying wind speed at 10 cm above surface, m/sec
T_a	= air temperature, °C
ρ_a	= density of air, a function of T_a , g/cm ³
ρ_w	= density of water, 1.0 g/cm ³
ν_a	= viscosity of air, a function of T_a , cm ² /s
ν_w	= viscosity of water, a function of T , cm ² /s
D_{OW}	= diffusivity of oxygen in water, a function of T , cm ² /s
κ	= von Karman's coefficient, 0.4
v_t	= transitional shear velocity (set to 10 assuming medium scales), cm/s
v_c	= critical shear velocity (set to 11 assuming medium scales), cm/s
z_e	= equivalent roughness (set to 0.35 assuming medium scales), cm
z_0	= effective roughness, a function of z_e , Γ , C_d , v_t , ν_a , and W , cm
λ	= inverse of Reynold's number (set to 3 assuming medium scales)
Γ	= nondimensional coefficient (set to 6.5 assuming medium scales)
Γ_u	= nondimensional coefficient, a function of Γ , v_c , C_d , and W
C_d	= drag coefficient, a function of z_e , Γ , ν_a , κ , v_t , and W

Equation 7-71 is used for wind speeds of up to 6 m/sec, where interfacial conditions are smooth and momentum transfer is dominated by viscous forces. Equation 7-73 is used for wind speeds over 20 m/sec, where interfacial conditions are rough and momentum transfer is dominated by turbulent eddies. Equation 7-72 is used for wind speeds between 6 and 20 m/sec, and represents a transition zone in which the diffusional sublayer decays and the roughness height increases.

The user is referred to O'Connor (1983) for details on the calculation of air density, air and water viscosity, the drag coefficient, the effective roughness, and Γ_u . Small scale represents laboratory conditions. Large scale represents open ocean conditions. Medium scale represents most lakes and reservoirs. The formulations in EPD-RIV1 assume that the scale is medium. Also, note that the wind speed is input in units of mi/hr and is converted by the code to m/s for use in the above equations. **Also, note that the larger of the two reaeration coefficients (K2 and KW) will be used in the computation of the reaeration rate in Equation 7-60. Also note that if the user specifies the option QWIND0=FALSE, then wind reaeration will not be considered.**

7.3.7.2.3. Structural Reaeration

Reaeration over structures can also be simulated by EPD-RIV1. **The model will compute structural reaeration if the user selects this option by setting IDAM0 = yes in input.** The increase in dissolved

oxygen is computed based upon the structural reaeration equations from Wilhelm and Smith's formulation for reaeration through gated-conduits

$$\left(\begin{array}{c} \text{DO following} \\ \text{structural reaeration} \\ \text{g O}_2 / \text{m}^3 \end{array} \right) = \text{DOSAT} \left[1 - \text{EXP} \left(- \left| \Delta H \right| \text{ DAMK } 1.022^{(\text{TEMP}-20)} \right) \right] + \text{DO} \left[\text{EXP} \left(- \left| \Delta H \right| \text{ DAMK } 1.022^{(\text{TEMP}-20)} \right) \right]$$

Equation 7-74

where

DAMK = reaeration coefficient, m
 TEMP = temperature, °C
 ΔH = elevation change, m
 DOSAT = saturation DO concentration, g/m³

and where the exponential term represents the ratio of the final to initial DO deficit. **Note that the coefficient DAMK is input with units of ft⁻¹ and then converted to m⁻¹ in the program.**

7.3.7.3. IRON AND MANGANESE OXIDATION

The oxidation of reduced iron (FE) and manganese (Mn) is considered to occur as a first-order reaction. Accounting for stoichiometric conversions, the oxygen used during oxidation of reduced iron and manganese is

$$\left(\begin{array}{c} \text{Rate of oxygen used} \\ \text{for oxidation of Fe} \\ \text{and Mn, g O}_2 / \text{m}^3 / \text{day} \end{array} \right) = -\text{OFEDEC} * \text{KFEDK} * \text{FE} - \text{OMNDEC} * \text{KMNDK} * \text{Mn}$$

Equation 7-75

where

OFEDEC = oxygen-to-iron ratio for iron oxidation
 KFEDK = oxidation rate for iron, day⁻¹
 FE = concentration of reduced iron, g/m³
 OMNDEC = oxygen-to-manganese ratio for manganese oxidation
 KMNDK = oxidation rate for manganese, day⁻¹
 Mn = concentration of reduced manganese, g/m³

7.3.7.4. SEDIMENT DEMAND

A DO loss for sediment oxygen demand (SOD) is also provided as a zero-order sink term. SOD is input by the user as KSOD, g/m²/day.

7.3.7.5. COMPLETE DO BALANCE

The complete balance of DO reactions is

$$\begin{aligned}
 & \left(\begin{array}{c} \text{Net rate of accumulation} \\ \text{of dissolved oxygen,} \\ \text{g / m}^3 \text{ / d} \end{array} \right) = \begin{array}{l} \text{(Reaeration) - (CBOD oxidation)} \\ - \text{(nitrification) + } \left(\begin{array}{c} \text{DO production} \\ \text{from algae / macrophytes} \end{array} \right) \\ - \left(\begin{array}{c} \text{DO used in algal /} \\ \text{macrophyte respiration} \end{array} \right) - \text{(Fe oxidation)} \\ \text{(Mn oxidation) - (SOD)} \end{array}
 \end{aligned}$$

Equation 7-76

This is stated in equation form as

$$\begin{aligned}
 \left(\begin{array}{l} \text{Rate of accumulation} \\ \text{of dissolved oxygen} \\ \text{g O}_2 / \text{m}^3 / \text{day} \end{array} \right) &= K_2 * (\text{DOSAT} - \text{DO}) - K_1 * \text{CBOD} - \text{ONITRI} * \text{KN} * \text{NH}_4\text{N} \\
 &+ \text{OPDECY} + \left[\text{ONEQUI} * \left(\frac{\text{NO}_3^- - \text{N}}{(\text{NO}_3^- - \text{N} + \text{NH}_4^+ - \text{N})} \right) \right] * (\text{ALGRO} + \text{MGRATE}) \\
 &- \text{OPDECY} * (1 - \text{FCBOD}) * (\text{ALGADK} + \text{MDEATH}) - \text{OFEDEC} * \text{KFEDK} * \text{FE} \\
 &- \text{OMNDEC} * \text{KMNDK} * \text{MN} - \text{KSOD}
 \end{aligned}$$

Equation 7-77

7.3.7.6. PARAMETERS AND CONSTANTS SPECIFIED FOR DISSOLVED OXYGEN

Table 7-6. Parameters and Constants affecting Dissolved Oxygen

1) Parameters that can appear in the Global Constants Cards			
Name	Explanation	Typical Value	Reference
ICOVAR	Option of using Covar's technique (0=no, 1 = yes)	-	
SATOPT	Saturation equation option. If SATOPT=1, saturation computed using Elmore and Hayes (1960) formulation, otherwise using APHA (1985).	-	
IOPT_EL	Option for correcting the DO saturation by study area elevation.	-	
ELEV0	Base elevation (ft, from MSL) of study area		
TH_K2	Temperature coefficient for reaeration	1.024	Brown and Barnwell 1987
TH_SOD	Temperature coefficient for sediment oxygen demand	1.065	Thomann and Mueller 1987
ONITRI	Oxygen-to-nitrogen ratio for ammonia oxidation	4.57	Environmental Laboratory 1995
OPDECY	Oxygen-to-biomass ratio for oxygen production by algae and macrophytes when ammonia is the nitrogen source	1.59	Environmental Laboratory 1995
OFEDec	Oxygen-to-iron ratio for iron oxidation		
OMNDEC	Oxygen-to-manganese ratio for oxidation		
ONEQUI	Incremental increase in oxygen-to-algal biomass ratio for oxygen production by algae and macrophytes when nitrate is used as a nitrogen source	0.35	Environmental Laboratory 1995
2) Parameters that can appear in the Branch Constants Cards			
Name	Explanation	Typical Value	Reference
IDAM0	Option of using dam reaeration (0=No, 1 =Yes)	-	
DAMK0	Dam Reaeration Coefficient (ft ⁻¹)	0.045	Wilhelm and Smith 1981
QWIND0	Logical variable to specify if wind driven reaeration is to be used for this segment (T or F)	-	
3) Parameters that vary by node			
Name	Explanation	Typical Value	Reference
KREAR	Rate coefficient for reach specific reareation m day ⁻¹		
AG	Rate coefficient for stream reaeration rate		

E1	Exponent of velocity in stream reaeration rate formulation		
E2	Depth exponent in stream reaeration formulation		
TSIV	Coefficient in the Tsivoglou-wallace reaeration equation, ft^{-1}	0.054	Environmnetal Laboratory 1995
SOD	Rate coefficient for sediment oxygen demand, $\text{g m}^{-2} \text{ day}^{-1}$	0.05-10	Thomann and Mueller 1987

7.3.8. Iron and Manganese

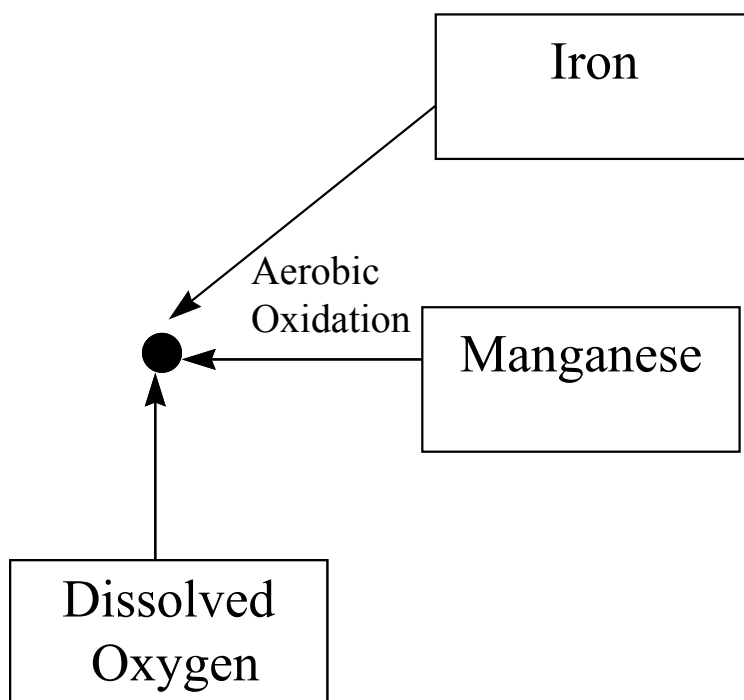


Figure 7-8

As modeled in EPD-RIV1, iron and manganese have no autochthonous sources. They can enter the system only in reduced form from upstream boundaries, tributaries, and lateral inflows. Oxygen depletion resulting from the oxidation of these reduced metals may have an adverse impact on water quality downstream from the inflow source. Since the presence of reduced metals probably accompanies releases of waters already somewhat depleted of DO, metal oxidation may exacerbate existing conditions.

Oxidation of reduced iron or manganese (loss from the system) is treated simply as a first-order process.

$$\left(\begin{array}{c} \text{Loss of Mn} \\ \text{due to oxidation} \\ \text{g/ m}^3 / \text{day} \end{array} \right) = -\text{KMNDK} * \text{MN}$$

$$\left(\begin{array}{c} \text{Loss of Fe} \\ \text{due to oxidation} \\ \text{g/ m}^3 / \text{day} \end{array} \right) = -\text{KFEDK} * \text{FE}$$

Equation 7-78

Oxidation does not occur if DO is less than the user-specified value of OXIDAT. Use of Equation 7-78 may require field data to estimate oxidation (i.e., decay) rates.

Temperature does not affect the oxidation rates in the model. Such rate corrections are unnecessary since the current model formulation does not account for other, possibly more important effects such as pH and auto-catalysis.

7.3.8.1. PARAMETERS AND CONSTANTS FOR IRON AND MANGANESE

Table 7-7. Parameters and Constants affecting Iron and Manganese

1) Parameters that can appear in the Global Constants Cards			
Name	Explanation	Typical Value	Reference
None			
2) Parameters that can appear in the Branch Constants Cards			
Name	Explanation	Typical Value	Reference
KMNDK	Specific rate coefficient for manganese oxidation, day ⁻¹		
KFEDK	Specific rate coefficient for iron oxidation, day ⁻¹		
OXIDAT	D.O. concentration below which oxidation of iron and manganese do not occur, mg/l		
3) Parameters that vary by node			
Name	Explanation	Typical Value	Reference

None			
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7.3.9. Coliform Bacteria and Arbitrary Constituents

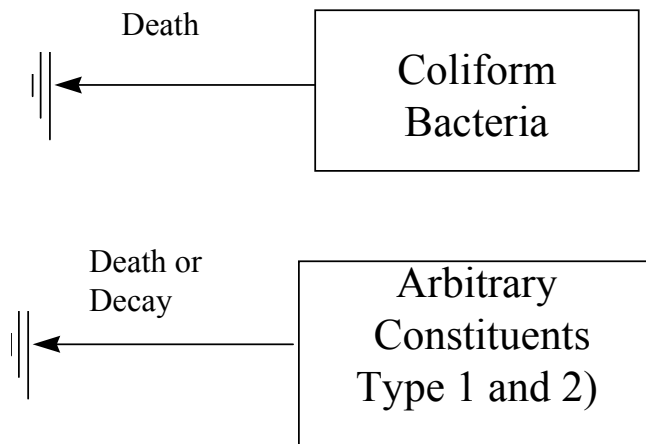


Figure 7-9

Fecal coliform bacteria, which are a preferred indicator of total coliform bacteria, enter the system only through inflows that represent agricultural or urban flows. Fecal coliforms do not reproduce in natural aquatic environments, and their populations decay exponentially; thus

$$\left(\begin{array}{c} \text{Loss of fecal coliforms,} \\ \text{colonies/ 100 ml/ day} \end{array} \right) = -KCOLIDK * COLI * TH_COLIF^{(TEMP-20.)}$$

Equation 7-79

where

KCOLIDK = rate coefficient for fecal coliform die-off, day⁻¹

COLI = fecal coliform count, colonies/100 ml

TEMP = temperature, °C

TH_COLIF = temperature coefficient.

There are two arbitrary constituents included in EPD-RIV1. The loss rates of the arbitrary constituents are computed from

$$\left(\begin{array}{c} \text{Loss of Constituent} \\ \text{g / m}^3 \text{ day} \end{array} \right) = -AKARB * ARB * TH_ARB1^{(TEMP-20)}$$

Equation 7-80

where

AKARB = rate coefficient for decay of the arbitrary constituent (1 or 2), day⁻¹

ARB = concentration of arbitrary constituent

TH_ARB1 = temperature coefficient

There is a set of each of the above variables for each of the two arbitrary constituents (e.g. AKARB1 and AKARB2). The arbitrary constituent variables C(15,I) and C(16,I) can be used for modeling miscellaneous non-conservative or conservative constituents (by setting AKARB = 0) since they do not interact with other water quality variables.

7.3.9.1. PARAMETERS AND COEFFICIENTS FOR COLIFORM BACTERIA AND ARBITRARY CONSTITUENTS

Table 7-8. Parameters and Constants affecting Coliform Bacteria and Arbitrary Constituents

1) Parameters that can appear in the Global Constants Cards			
Name	Explanation	Typical Value	Reference
TH_COLIF	Temperature coefficient for coliform mortality	1.047	Brown and Barnwell, 1987
TH_ARB1	Temperature coefficient for decay of arbitrary constituent 1	Variable	
TH_ARB2	Temperature coefficient for decay of arbitrary constituent 2	Variable	
2) Parameters that can appear in the Branch Constants Cards			
Name	Explanation	Typical Value	Reference
AKARB1	Rate coefficient for arbitrary constituent 1, day ⁻¹	Variable	
AKARB2	Rate coefficient for arbitrary constituent 2, day ⁻¹	Variable	
3) Parameters that vary by node			
Name	Explanation	Typical Value	Reference
KCOLIDK	Rate coefficient for coliform mortality, day ⁻¹	0.05-4.0	Brown and Barnwell, 1987

7.4. The Numerical Solution For Constituent Transport

7.4.1. The Governing Equation

The general form of the equation to be solved is, for a mass concentration α

$$\frac{\partial(A\alpha)}{\partial t} + \frac{\partial(UA\alpha)}{\partial x} = \frac{\partial}{\partial x} \left(DA \frac{\partial \alpha}{\partial x} \right) + q\gamma + S^*$$

Equation 7-81

where

D = dispersion coefficient
 γ = concentration of the runoff input to the channel by distributed flow q
 S^* = source/sink term which accounts for changes in α due solely to biological and chemical reactions

The variable S^* is decomposed into a source/sink term that is a function of the present concentration of α and a function that is not; therefore

$$\frac{\partial(A\alpha)}{\partial t} + \frac{\partial(Q\alpha)}{\partial x} = \frac{\partial}{\partial x} \left(DA \frac{\partial \alpha}{\partial x} \right) + q\gamma + AC_1\alpha + AC_2$$

Equation 7-82

where C_1 has units of (1/t) and C_2 has units of (M/L³t). This is the form of the equation to be solved, and it requires the initial and boundary conditions. After chain rule differentiation, the governing equation is reassembled in the form

$$\frac{\partial \alpha}{\partial t} + U \frac{\partial \alpha}{\partial x} + \frac{\alpha}{A} \frac{\partial U}{\partial x} - \left(\frac{D}{A} \frac{\partial A}{\partial x} + \frac{\partial D}{\partial x} \right) \frac{\partial \alpha}{\partial x} = D \frac{\partial^2 \alpha}{\partial x^2} - \varphi_1 \alpha + \varphi_2$$

where

$$\varphi_1 = \left(\frac{1}{A} \frac{\partial A}{\partial t} + \frac{U}{A} \frac{\partial A}{\partial x} - C_1 \right)$$

Equation 7-83

and

$$\varphi_2 = \left(C_2 + \frac{q\gamma}{A} \right)$$

Equation 7-84

Equation 7-82 can be rewritten

$$\frac{\partial \alpha}{\partial t} + \bar{u} \frac{\partial \alpha}{\partial x} = D \frac{\partial^2 \alpha}{\partial x^2} - \varphi_1 \alpha + \varphi_2 - \alpha \frac{\partial U}{\partial x}$$

Equation 7-85

where

$$\bar{u} = U - \left(\frac{\partial D}{\partial x} + \frac{D}{A} \frac{\partial A}{\partial x} \right) = U - DDA$$

Equation 7-86

and

$$DDA = \frac{\partial D}{\partial x} + \frac{D}{A} \left(\frac{\partial A}{\partial x} \right)$$

Equation 7-87

From continuity

$$\frac{\partial A}{\partial t} + A \frac{\partial U}{\partial x} + U \frac{\partial A}{\partial x} = q$$

Equation 7-88

Using Equation 7-88, the second and fourth terms on the right side of Equation 7-85 can be combined as

$$-\alpha \left(-1 + \frac{\partial U}{\partial x} \right) = -\alpha \left(\frac{q}{A} - C_1 \right)$$

Equation 7-89

and φ_1 is redefined as

$$\varphi_1 = \frac{q}{A} - C_1$$

Equation 7-90

Thus Equation 7-85 becomes

$$\frac{\partial \alpha}{\partial t} + u \frac{\partial \alpha}{\partial x} = D \frac{\partial^2 \alpha}{\partial x^2} - \varphi_1 \alpha + \varphi_2$$

Equation 7-91

The φ_1 and φ_2 terms of Equation 7-91 are written in expanded form so that they can be followed more easily in the code; thus

$$\frac{\partial \alpha}{\partial t} + u \frac{\partial \alpha}{\partial x} = D \frac{\partial^2 \alpha}{\partial x^2} + \frac{q}{A} (\gamma - \alpha) - K_s \alpha + \text{SINKS}$$

Equation 7-92

where

K_s = $-C_1$ = biochemical uptake or decay rates (+) and growth rates (-)
 SINKS = C_2 = biochemical sources (+) and sinks (-)

The left side of Equation 7-92 is solved for the new time level value of α (α^{j+1})

with the fourth-order explicit scheme. Using this new value, α^{j+1}

α^{j+1} is incremented due to the effects of the second, third, and fourth terms on the right side of Equation 7-92. The $SINKS$ and K_s values are interpolated values between nodes (see Equation 7-97). Finally, the solution is completed by adding the effect of diffusion (first term on right side of Equation 7-92), which is computed implicitly.

7.4.2. Fourth-Order Explicit Scheme

The compact, fourth-order accurate scheme presented by Holly and Preissman (1978) is a satisfactory scheme for 1-D advection calculations and is used for all mass transport calculations.

7.4.2.1. POLYNOMIAL ASSUMPTION

It is assumed that the variation of any quantity between two adjacent spatial nodes is not linear but is depicted by a cubic polynomial such that for a variable Y

$$Y(\xi) = A\xi^3 + B\xi^2 + D\xi + E$$

Equation 7-93

where

$$\xi = \frac{u^* \tau}{X_{i+1} - X_i}$$

where

u^* = average characteristic velocity
 τ = time-step $t_{i+1} - t_i$

The coefficients for the polynomial are evaluated from the conditions that

$$Y(1) = \alpha_i^j ; Y(O) = \alpha_{i+1}^j ; \dot{Y}(1) = \alpha x_i^j ; \dot{Y}(O) = \alpha x_{i+1}^j$$

$$\alpha x = \frac{\partial \alpha}{\partial x}$$

$$\dot{Y}(\xi) = \left. \frac{dY}{dx} \right|_{\xi}$$

Equation 7-94

After some algebra

$$Y(\xi) = A_1 \alpha_i^j + A_2 \alpha_{i+1}^j + A_3 \alpha x_i^j + A_4 \alpha x_{i+1}^j$$

Equation 7-95

where

$$A_1 = \xi^2(3 - 2\xi)$$

$$A_2 = 1 - A_1$$

$$A_3 = \xi^2(1 - \xi)(x_{i+1} - x_i)$$

$$A_4 = -\xi(1 - \xi)^2(x_{i+1} - x_i)$$

Note that since the polynomial is parameterized by first derivatives, an equation for the first derivatives is also necessary. A polynomial for the first derivatives is formed from

$$\dot{Y}(\xi) = b_1 \alpha_i^j + b_2 \alpha_{i+1}^j + b_3 \alpha x_i^j + b_4 \alpha x_{i+1}^j$$

Equation 7-96

where

$$b_1 = 6\xi(\xi - 1)(x_{i+1} - x_i)^{-1}$$

$$b_2 = -b_1$$

$$b_3 = \xi(3\xi - 2)$$

$$b_4 = (\xi - 1)(3\xi - 1)$$

Both

$Y(\xi)$

and

dY/dx

.

$\left(\frac{\xi}{\alpha}\right)^{j+1}$ will be used to determine

αx_{i+1}^{j+1} and αx_{i+1}^{j+1} , respectively, resulting from pure advective transport (the left side of Equation 7-92).

7.4.2.2. SOLUTION PROCEDURE FOR α_{i+1}^{j+1}

Any variable or coefficient can be interpolated to obtain the average value between nodes as

$$K^* = \frac{[K_{i+1}^{j+1} + K_{i+1}^j (1 - \xi) + K_i^j \xi]}{2}$$

Equation 7-97

where

$$\xi = \frac{u^* \tau}{x_{i+1} - x_i}$$

Equation 7-98

and u^* is the average characteristic velocity between nodes. Likewise, u^* can be found by placing a linear interpolation between \bar{u} and \bar{u}_{i+1} , based on u^* , or from Equation 7-97

$$u^* = \frac{\left[\bar{u}_{i+1}^{j+1} + \bar{u}_{i+1}^j - \left(\frac{u^* \tau}{x_{i+1} - x_i} \right) (\bar{u}_{i+1}^j - \bar{u}_i^j) \right]}{2}$$

Equation 7-99

solving for u^* and substituting Equation 7-86 for \bar{u}

$$u^* = \frac{U_{i+1}^{j+1} + U_{i+1}^j - DDA_{i+1}^{j+1} - DDA_{i+1}^j}{2 + \frac{\tau}{x_{i+1} - x_i} (U_{i+1}^j - U_i^j)}$$

Equation 7-100

The term $\partial DDA / \partial x$ becomes zero since D and A are allowed only linear variations between nodes.

The value of α_{i+1}^{j+1} due to advection, α_{i+1}^{**} , can now be determined from

$$\alpha_{i+1}^{**} = Y(\xi)$$

Equation 7-101

where $Y(\xi)$ is evaluated by Equation 7-95. The values for αx_i^j and αx_{i+1}^j in Equation 7-95 must be determined from

$$\alpha x_{i+1}^j = \dot{Y}(\xi)$$

Equation 7-102

for Equation 7-96. The decay, sources/sinks, and lateral inflow terms are next added to α_{i+1}^{**} such that

$$\alpha_{i+1}^{j+1} = \alpha_{i+1}^{**} (1 - \tau K_s) + \tau \left[\text{SINKS} + \frac{q}{A} (\gamma - \alpha_{i+1}^{**}) \right]$$

Equation 7-103

7.4.2.3. SOLUTION PROCEDURE FOR αx_{i+1}^{j+1}

A spatial derivative of the transport equation must be developed to update αx_{i+1}^{j+1} . This development is done by taking the derivative of Equation 7-92 with respect to x ,

$$\frac{\partial \alpha'}{\partial t} + \bar{u} \frac{\partial^2 \alpha'}{\partial x} = D \frac{\partial^2 \alpha'}{\partial x^2} - \bar{u}' \alpha' + \left(\frac{q}{A} \right) (\gamma - \alpha) - \frac{q}{A} \alpha' - k_s \alpha' + \text{SINKS}'$$

Equation 7-104

where

$$\bar{u} = \bar{u} - D'$$

and the prime denotes

$$\frac{\partial}{\partial x}$$

; thus α'

$\frac{\partial \alpha}{\partial x} = \alpha_x \equiv \alpha_x$. Now

$\bar{u} = U'$ since D and A are allowed only linear variations between nodes. If D' is small and D at a node is constant or changes slowly over time, the characteristic velocity for the spatial gradient is approximated by $u^{**} = \bar{u} - D'$. With the value u^{**} , ξ^* can be determined from

$$\xi^* = \frac{\tau u^{**}}{X_{i+1} - X_i}$$

Equation 7-105

Now $\bar{Y}(\xi^*)$ can be evaluated through Equation 7-96. This evaluation yields

$$\alpha_x^{**}$$

$$\equiv Y^{i+1}$$

(ξ^*) , which is the solution to the left side of Equation 7-104. All but the first term on the right side of Equation 7-104 are added to α_{i+1}^{**} such that

$$\alpha_{i+1}^{j+1} = \alpha_{i+1}^{**} \left[1 - \frac{\tau (U_{i+1}^j - U_i^j)}{X_{i+1} - X_i} - \tau \left(K_s + \frac{q}{A} \right) \right] + \tau \left[\left(\frac{q}{A} \right)' (\gamma - \alpha) - \alpha K'_s + \text{SINKS}' \right]$$

Equation 7-106

The final update for α_{i+1}^{j+1}

is completed when the implicit solution due to the first term on the right side of Equation 7-104 (diffusion) is added.

The derivatives for coefficients used in Equation 7-104 to Equation 7-105 are found by

$$\frac{\partial K^j}{\partial x} \cong \frac{K_{i+1}^j - K_i^j}{X_{i+1} - X_i}$$

Equation 7-107

and

$$\frac{\partial^2 K^j}{\partial x^2} \cong \frac{\left(\frac{\partial K^j}{\partial x} \right)_{i+1} - \left(\frac{\partial K^j}{\partial x} \right)_i}{X_{i+1} - X_i}$$

Equation 7-108

The steps outlined in this section are repeated for each spatial node before moving on to the next time line.

7.4.3. Implicit Diffusion

The constituent transport (Equation 7-92) and the spatial derivative transport (Equation 7-104) equations are now ready to have the effects of diffusion added by

$$\alpha_i^{j+1} = \alpha_i^j + \tau D \frac{\partial^2 \alpha}{\partial x^2}$$

$$\alpha_{x_i}^{j+1} = \alpha_{x_i}^j + \tau D \frac{\partial^2 \alpha'}{\partial x^2}$$

Equation 7-109

where now the j time-level is actually at the new time-level following the advection and kinetic reactions but just prior to diffusion. The diffusion terms are approximated by difference equations, approximately centered in space and time. That is, new time information ($j+1$) is weighted by a factor $\theta = 0.55$ to enhance stability. The second derivative is replaced by the difference operator D_{xx} ; thus

$$\frac{\partial^2 \alpha}{\partial x^2} = \theta D_{xx}(\alpha^{j+1}) + (1 - \theta) D_{xx}(\alpha^j)$$

Equation 7-110

In space, centering would be exact for a regular grid. However, with an irregular grid, a quadratic interpolation is used by taking a Taylor series such that

$$D_{xx}(\alpha) = 2 \left[\frac{\alpha_{i+1} - \alpha_i}{\Delta x_i (\Delta x_{i-1} + \Delta x_i)} + \frac{\alpha_{i-1} - \alpha_i}{\Delta x_{i-1} (\Delta x_{i-1} + \Delta x_i)} \right]$$

Equation 7-111

where $\Delta x_i = x_{i+1} - x_i$

Applying Equation 7-111 to the difference operator (Equation 7-110) which is subsequently applied to Equation 7-109 results in Equation 7-112 104 for α_i^{j+1} ,

$$\alpha_i^{j+1} = \alpha_i^j + 2\tau D\theta \left[\frac{\alpha_{i+1}^{j+1} - \alpha_i^{j+1}}{\Delta x_i(\Delta x_{i-1} + \Delta x_i)} + \frac{\alpha_{i-1}^{j+1} - \alpha_i^{j+1}}{\Delta x_{i-1}(\Delta x_{i-1} + \Delta x_i)} \right] \\ + 2\tau D(1 - \theta) \left[\frac{\alpha_{i+1}^j - \alpha_i^j}{\Delta x_i(\Delta x_{i-1} + \Delta x_i)} + \frac{\alpha_{i-1}^j - \alpha_i^j}{\Delta x_{i-1}(\Delta x_{i-1} + \Delta x_i)} \right]$$

Equation 7-112

An equation similar to Equation 7-112 is developed for α_{i+1}^{j+1} .

When Equation 7-112 is applied to every node for i going from 2 to $N-1$, $N-2$ equations for N unknowns are formed. The system is completed by the upstream and downstream boundary conditions. The upstream boundary condition is given explicitly in the data (or inferred for the spatial derivative of diffusion). The downstream boundary condition is simply that the last node is not affected by diffusion.

The system of equations is assembled in tridiagonal form with all new values ($j+1$) on the left side and all old (j) values on the right. The implicit solution is accomplished with the Thomas Algorithm (subroutine TRIDAG). Subroutine TRIDAG is also used to calculate a cubic spline through the initial data.

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9. APPENDIX A: EXAMPLE TUTORIAL APPLICATION NUMBER 1

9.1. INTRODUCTION

The following analysis is designed to provide an example of an application of the EPD-RIV1 modeling system that is reasonably realistic but not so complex that it detracts from the example's principal intent, which is to

- demonstrate the major steps of assembling and modifying environmental data for input into EPD-RIV1, and
- demonstrate the application of each of the major components of the EPD-RIV1 modeling system.

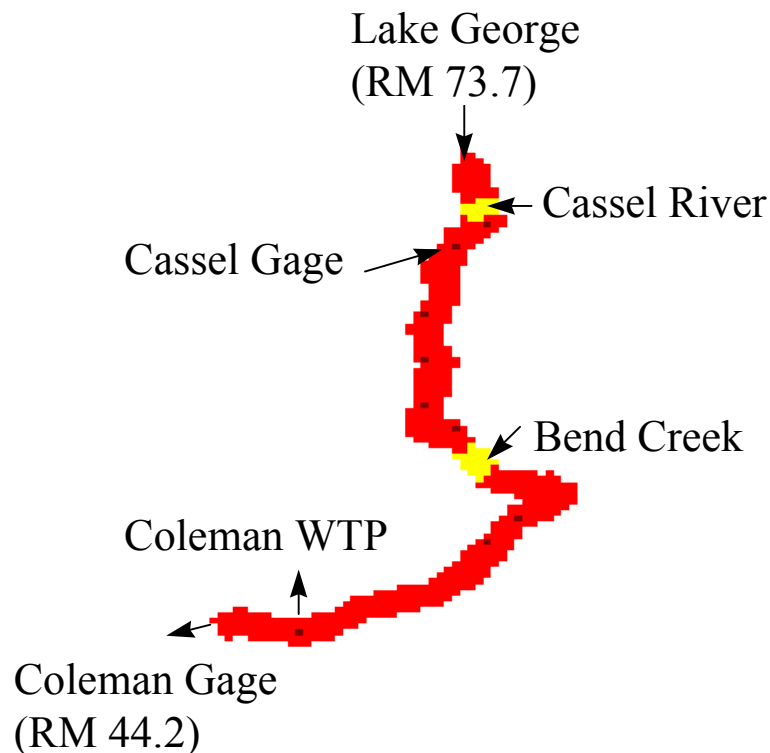
The data on which this example is based are taken from several model applications and then consolidated or modified for this example. However, the reader should not infer that this example is either representative of a typical model application or provides detailed guidance in the data requirements for a particular application. Data requirements, and the judgments that must be made for an application, are site-specific

9.2. PROBLEM SETTING AND RIVER CHARACTERISTICS

In this example, a reservoir is located at the headwaters of a medium size river. The river receives water from an upstream reservoir that is operated primarily to provide for low flow augmentation. The river is used locally for recreation, such as fishing and swimming, and is bordered by several campgrounds. There is a water supply intake located 26.8 miles downstream, at River Mile 46.9, and this location is the principal focus for water quality. In addition, there is some concern as to the potential impact of nutrients on the quality. The river receives inflows from two major tributaries:

- Cassel River
- Bend Creek

of which Cassel River is gaged. Limited (monthly) flow estimates are available for Bend Creek.



The river is also gaged by the USGS immediately below the dam . A USGS gaging station is also located at River Mile 70.6, 3.1 miles below the dam, and below the water supply intake at River Mile 44.2, 29.5 miles below the dam.

The designated used classification for the river is:

- Lake George to Bend Creek: Recreation and Fishing

- Bend Creek to Coleman WTP: Recreation and Drinking Water

The applicable standards are listed below:

Drinking Water: the criteria for drinking water, waters approved as a source for public drinking water systems, are provided below. Waters classified for drinking water supplies will also support the fishing use and any other use requiring water of a lower quality.

- **Bacteria:** For the months of May through October, when water contact recreation activities are expected to occur, fecal coliform not to exceed a geometric mean of 200 per 100 ml based on at least four samples collected from a given sampling site over a 30-day period at intervals not less than 24 hours. For the months of November through April, fecal coliform not to exceed a geometric mean of 1,000 per 100 ml based on at least four samples collected from a given sampling site over a 30-day period at intervals not less than 24 hours and not to exceed a maximum of 4,000 per 100 ml for any sample.
- **Dissolved oxygen:** A daily average of 5.0 mg/l and no less than 4.0 mg/l at all times.
- **pH:** Within the range of 6.0 - 8.5.
- **Temperature:** Not to exceed 90F. At no time is the temperature of the receiving waters to be increased more than 5F above intake temperature.

Recreation: Recreational uses include activities such as water skiing, boating, and swimming, or for any other use requiring water of a lower quality, such as recreational fishing. Relevant criteria include:

- **Bacteria:** Fecal coliform are not to exceed a geometric mean of 200 per 100 ml based on at least four samples collected from a given sampling site over a 30-day period at intervals not less than 24 hours. Should water quality and sanitary studies show natural fecal coliform levels exceed 200/100 ml (geometric mean) occasionally in high quality recreational waters, then the allowable geometric mean fecal coliform level shall not exceed 500 per 100 ml in free flowing fresh water streams.

- Dissolved Oxygen: A daily average of 5.0 mg/l and no less than 4.0 mg/l at all times for waters supporting warm water species of fish.
- pH: Within the range of 6.0 - 8.5.
- Temperature: Not to exceed 90F. At no time is the temperature of the receiving waters to be increased more than 5F above intake temperature.

In addition to the water quality criteria, there is some concern as to the impact of nutrients transported to a downstream reservoir resulting in increased eutrophication.

9.3. REVIEW AND COMPILATION OF ENVIRONMENTAL DATA

The first step in the application of EPD-RIV1 to the Youg river was the review and compilation of environmental data. It was decided that for the purposes of this study, based upon an analysis of historical data and review of available data, that **simulations would be performed for the period of May to November, 1995**, and data were compiled for that period. Available data included:

- Weekly measurements of BOD5, ammonia-nitrogen, nitrate-nitrogen, ortho-phosphorus, coliform bacteria, and dissolved iron below the Lake George dam, from March 7 to December 25, 1995.
- Daily measurements of flows, water temperatures, and dissolved oxygen concentrations below the Lake George dam, from March 2 to December 26, 1995.
- Daily flow measurements and weekly measurements of water temperatures, BOD5, ammonia-nitrogen, nitrate-nitrogen, organic nitrogen, ortho-phosphorus, organic phosphorus, coliform bacteria, and dissolved oxygen in the Cassel River above its confluence with the Yough, from January 4 to December 25, 1995

- Daily stage measurements at the Cassel Gage located in the main stem river at River Mile 70.6, 3.1 miles below the dam, from May 5 to October 38, 1995.
- Monthly measurements, from January to December 1995, of flow, water temperatures, BOD5, ammonia-nitrogen, nitrate-nitrogen, organic phosphorus, ortho-phosphorus, coliform bacteria, and dissolved oxygen at a station located in Bend Creek above its confluence with the Yough River at River Mile 60.4.
- Weekly measurements, from May 7 to December 28, 1995, of water temperature, and concentrations of dissolved oxygen, BOD5, ammonia-nitrogen, nitrate-nitrogen, ortho-phosphorus, and coliform bacteria at a station located at the Cassel Gage in the main stem river at River Mile 70.6 and below the confluence of the Cassel and Yough Rivers.
- Daily flows in the Yough River at the USGS Coleman gage, located at River Mile 29.5, from May 1 to October 29, 1995.
- Hourly measurements of water temperatures and dissolved oxygen concentrations, and weekly measurements of BOD5, ammonia-nitrogen, ortho-phosphorus, and coliform bacteria at a station located immediately below the water supply intake for the period of May 6 to October 29, 1995.
- Hourly meteorological data from the city of George, located 35 miles from the project, for the period of January 2 to December 29, 1995.
- Withdrawal rates for the WTP at 4-hour intervals for January to December 1995.

Daily flows were available which could be used as the model downstream boundary condition. However, it may be necessary to perform simulations using different (estimated) upstream boundary conditions than those measured. Additionally, downstream flow boundary conditions are generally not recommended for rivers. Instead, the USGS was contacted and the rating curve for the site

obtained. The rating curve will be used as the downstream boundary condition.

Constituents of concern included temperature, coliform bacteria and dissolved oxygen. Since the impact of nutrient loadings on a downstream reservoir was of concern, it was also determined that nitrogen and phosphorus species should also be simulated.

The review of indicated that available data were not adequate to describe the river's geometry. Only limited cross-sectional data were available. Maps and a site inspection were used to identify critical points in the river, and points that best approximated the average cross-sectional characteristics. Since average velocities in the river were on the order of 1 ft/sec, and the river was relatively uniform in its shape, it was estimated that cross-sections located 1-2 miles apart would provide adequate resolution for the quality simulations. The river was surveyed at 18 locations and the survey records converted to the EPD-RIV1 input format.

All data were reviewed and then placed into a database from which they could be extracted for input to EPD-RIV1.

9.4. PREPARATION AND ENTRY OF ENVIRONMENTAL DATA

The second step in the application of EPD-RIV1 to the Young river was preparation of model input data files. The input files required include the:

- Project File
- Hydrodynamic Model Input File
- Water Quality Model Input File
- Auxiliary Files:
 - Boundary Condition File

- Lateral Input File
- Meteorological Data
- Cross-Sectional Geometry File
- Withdrawal File

For this application there are no power plants in the river reach, so a power plant file was not required.

The sequence of steps involved in preparing the various files may vary between users. All of the files may be created in a single session, or in a series of steps. The following provides

9.4.1. Creating Time-Varying Auxiliary Files Using the DELIBERATOR

For this application, four time-varying data input files must be created:

- **Upstream Boundary Condition File:** This file will be based on time varying information taken below the Youg Dam.
- **Lateral Input File:** The time-varying data from the Cassel River and Bend Creek will be provided to the model as lateral inflows.
- **Withdrawal File:** This file will be based upon the recorded withdrawal rates from the Water Supply.
- **Meteorological Data Input File:** The time-varying meteorological data from the city of George.

All of these data were analyzed and placed in a data base for use by EPD-RIV1. The next step in the process is the manipulation of the data in the creation of model input data files. The primary remaining difficulty is that the data are available at varying frequencies, ranging from hours to months. For example, the data from the Youg Dam are available at daily frequencies for flows, water temperatures, and dissolved oxygen concentrations while only weekly values are available for the remaining constituents. Since EPD-RIV1 requires that



The auxiliary files require specification of **node numbers** which identify the locations where lateral inflows, withdrawals, etc., enter the model grid, and the expected node numbers ~~are those assigned by RIV1H~~. For a simple network, as in this example, the node numbers are simply the cross-section numbers beginning with one at the upstream boundary and increasing downstream. For a complicated network, it is best to create a hydrodynamic input file, run the model, and obtain the node numbers from the model output. If you do not know the node numbers when creating the auxiliary files, assign an approximate number now and then correct the number when editing the file in the Pre-Processor.



The auxiliary files are most commonly created using linear interpolation to ensure that all data are provided at the same frequency. As with any manipulated data, you should compare the interpolated data to the original data to ensure that the interpolated data accurately represent the original data

all data be on the same frequency in a particular input file, the data must be manipulated. This is a primary task of the DELIBERATOR.

To create the auxiliary files, the general steps are to:

- 1) Load the DELIBERATOR from the EPD-RIV1 shell.
- 2) Open the data base table containing information for this application (YOUG.DB).
- 3) Perform a query on the table to create a subset of the database containing only data needed for the particular input file. To illustrate one way by which this can be accomplished, the user would:
 - 4) Select a visual query
 - 5) Select the data table (YOUG.DB)
 - 6) Select the operator to perform the query on. In this case it would be STATION_ID.
 - 7) Select the type of query. For this example, if the user selects "is contained in" they would be provided a pick list of all of the Station ID codes from which they could select the appropriate site.

- 8) Select OK and then the DELIBERATOR would create a second table containing only the data for the selected Station ID.
- 9) Manipulate the data to create a data file. This may be accomplished by selecting Manipulate from the tool bar. For this example, we will require that the data be interpolated so that they will be on the same frequency. The user would then
- 10) Specify the start and end times for the manipulation and the frequency of the interpolation. The start and end times can be obtained by examining the database table.
- 11) Specify the file type (BCF, LAT, WIT, etc.) and interpolation option (linear or stair-stepped)
- 12) The user would then add a row to the table, select a database table (the new table from the query), and specify the node number.
- 13) The user would then select OK and the Deliberator would process the file and, after completion query the user for a filename. This would complete the initial development of the boundary condition file.

9.4.1.1.CREATING THE BOUNDARY CONDITION FILE

Only one boundary condition file will be required for this application. The station ID for the boundary is YOUNG DAM, and data are available from March 2 to December 31, 1995, so this would be the time period. The most frequent data are hourly, so a 24 hour frequency can be used. The node number is one, which in this case indicated branch one, and the number is positive to indicate that it is an upstream boundary condition.

9.4.1.2.CREATING THE LATERAL INFLOW FILE

The lateral inflow file contains flows and their associated concentrations for each of the tributaries, point and non-point sources entering the model domain. For this example, there are two lateral inflows: Cassel River and Bend Creek.

The Lateral Inflow file may be created by following the steps outlined above used in the creation of the boundary condition file. Since there are two lateral inflows, the user would create two temporary subsets of the original data by performing first a query for the station ID of CASSEL RVR and then BEND CRK. The user would then select the interpolation option for manipulate and proceed as before, but:

- selecting LAT for the lateral file;
- inserting two lines into the table for manipulation representing each of the two temporary subsets (one for the Cassel River and one for Bend Creek);
- inserting the node numbers which, for the lateral inflows, is the node number at which the lateral inflow enters (2 for the Cassel and 10 for Bend Creek).
- specifying the interpolation frequency. For these data, the most frequent data are the daily flows, so the interpolation frequency would be 24 hours.

The user would then select OK and create the lateral inflow file. The Deliberator would then query the user for a file name.

9.4.1.3. CREATING THE WITHDRAWAL FILE

The withdrawal file would be created in a similar manner. However the withdrawal file only contains the withdrawal flows. The user would perform a query to subset the data with the Station ID COLE WTP, and then create the withdrawal file using the steps outlined above. For this example, the location of the withdrawal is node 16.

9.4.1.4. CREATING THE METEOROLOGICAL DATA INPUT FILE

The meteorological data contains a time series of cloud cover, wind speeds (miles/hr), air temperatures, dew point temperatures, and atmospheric pressures. These data are needed only if temperature is being simulated using a full heat balance. Up to five files may be used in a simulation, each representing a particular reach of the river. The

applicable reach is designated by specifying the beginning and end node to which the file applies.

For this example, only one meteorological input file will be used and all of the data are contained in the database in appropriate units. It is then only necessary to use the Deliberator to query the database to subset the file (Station ID = GEORGE CITY) and then create the file. Since hourly data are available, the user could use the interpolation option and select a frequency of one hour. This will result in the



In the Deliberator, there is no provision for specifying multiple nodes, such as the node from which and to which the meteorological data apply. There are also other data required to be in this file, such as the dust attenuation coefficient, latitude, longitude, and the longitude of the standard meridian. The additional, data must be added when editing the file in the Pre-processor.

output being on a even hourly frequency.

9.4.2. Using the Pre-Processor to Create the Project File and Main Input Files

In order to create input files for the hydrodynamic and water quality models, the user must first load the Pre-Processor from the Shell and Create a Project File. The Project File will contain the names and locations of the hydrodynamic and quality input files and the auxiliary files. The Project File can also contain a brief description of the project. Once the Project file has been created, then the main input files can be created. This would typically be accomplished by first creating the hydrodynamic file, running it and testing it and then creating the quality file.

9.4.2.1. CREATING THE HYDRODYNAMIC INPUT FILE

The data required by the hydrodynamic submodel to EPD-RIV1 include:

- Geometric information,
- Initial conditions
- Hydraulic and Control Parameters
- Forcing Functions
- Boundary Conditions
- Roughness coefficients,
- Lateral inflows
- Withdrawals

Once the geometric information has been obtained, it is then prepared for input to EPD-RIV1. The following information is required:

1. The **start and end times** for the hydrodynamic simulation are specified in the main input file. For this example, the year 1995 was selected for the simulation. Some data were available from the beginning of the year. However, the boundary data were only available for the period of March 2 to December 31, so that the simulation should be within this period.
2. The branch definition includes the number of branches, the branch name, the connectivity of the branch with downstream branches and the boundary conditions. In this case, there is only one branch. **For this example, since there is not a downstream branch, a zero is specified in the downstream branch and downstream cross-section input fields.** For this example, we will assign a flow at the upstream boundary. The time-flows will be provided in an auxiliary file, so the constant flow can be zero. We will assign a rating curve at the downstream boundary,

$$Q = 0.46 H^{0.11}$$

The coefficient for the rating curve (0.46) is specified in the place of the Downstream Boundary Value and the exponent of the rating curve in the place of the angle.

3. Under the **Run Parameters**, the river mile at the bottom of the branch may be specified. EPD-RIV1H will use this reference river mile to compute the location of the upstream cross-sections. For this example, **the location of the bottom cross-section of the Young river was river mile 44.2**. The remaining run parameters are the theta, tolerance, and momentum correction coefficient which should be left at default values.
4. Under **Results Interval**, the user specifies the frequency at which they wish to have the results displayed.
5. Under **Computational Time Step**, the user specifies the computational time step. For this example, we will use a constant 300 time seconds, estimated from the minimum travel time between two cross-sections.
6. The **cross-sections** are then defined in the hydrodynamic pre-processor. First, the number of cross-sections is determined, and for this example there are 18 cross-sections, so 18 cross-sections must be inserted. The geometric information required for each cross-section is then input, including the distance (ft.) from that cross-section to the next cross-section downstream, the bottom elevation of the cross-section, and the cross-sectional shape and/or name.



If the needed data, such as bottom elevations and lengths, are available in some other Windows application, such as a spreadsheet, you can cut and paste them into the cross-section tables in the pre-processor. If you are not used to the conventions for selecting cells and columns in the EPD-RIV1 tables, you will want to check your data carefully to make sure you pasted correctly. Also, try the fill/calculate option if you need to manipulate data.

- 1) The **distances and bottom elevations** (references to a common datum) were developed from maps and the field survey for this application. They are included in the spreadsheet file YOUNG.XLS and the text file YOUNG.TXT.

- 2) **Initial conditions** required by EPD-RIV1H **include flows and depths**. Initial estimates are also included in the Microsoft Excel spreadsheet and text file. The initial conditions do not have to be accurate, only sufficient to allow the model to run. The model can be run for a period to allow it to come into equilibrium and then better guesses of the initial conditions taken from the model output.



If you want to replace the initial conditions using results from a previous run, plot the flow and depth versus segment (XY plot) at the desired time and then create a table. Select the data and copy them into the cross-section tables in the preprocessor

- c. EPD-RIV1 can utilize **cross-sectional information** entered either in the form of equations relating area to depth or as tables of x-y pairs from which it will compute the relationships between areas and depths. For this application, the cross-sectional characteristics were input using look-up tables, so it is not necessary to specify coefficients (C1 to C3). However, the **lookup name for the cross-section must be specified**. A pick list of look up names is provided if an auxiliary cross-section file is selected. One approach would be to defer this step until the auxiliary files are selected and then come back to this step. Alternatively, the look up names are also included in the spreadsheet and text files, and may be taken from one of those sources.
- 1) The **constant lateral inflows** are zero for this example. The **energy loss coefficients** are also zero.
 - 2) The initial estimate of **Manning's** coefficient for this example was 0.05 for all cross sections. The coefficient was not varied by depth (N Coefficients 1 and 2 are zero).

- 3) It is desirable to have predicted information written to the output file for all of the cross-sections, so **all cross-section would be selected for output.**

9.4.2.2. CREATING THE WATER QUALITY INPUT FILE

The geometric data required by the quality model are provided in the hydrodynamic linkage file. The remaining information required in order to simulate water quality constituents include:

- Initial conditions
- Kinetics
- Global
- Branch
- Cross-Section
- Forcing Functions
- Boundary Conditions
- Lateral inflows
- Withdrawals, and
- Meteorological Data

Once the geometric information has been obtained, it is then prepared for input to EPD-RIV1. The following information is required:

1. The **start and end times** for the quality simulation are specified in the main input file. The start and end times for the hydrodynamic run are provided. The start and end times for the quality run must be within those for which hydrodynamic data will be available. It is usually best to start the quality simulations to start some time later than those for hydrodynamics in order to have time for the initial hydraulic conditions to “flush out”. For this example, we will start

the water quality simulations three days later than the hydrodynamic simulation.

2. Under **Plot**, the user specifies the frequency at which they wish to have the results written to the graphical output file.
3. Under **Bypass Options**, the user specifies which, if any, constituents are to be bypassed in the simulation. For this example, we will not simulate (bypass) NBOD or CBOD 2.
4. The **Kinetic** coefficients are then defined. There are three sets of kinetic coefficients: those applicable to the entire modeled system (**Global**), those applicable to a particular branch (**Branch**), and those applicable to a particular **cross-section**. For this example, the selection of the kinetic coefficients was made by reviewing the literature, available site-specific data, and studies of similar systems. The initial selection of the coefficient values were compiled in the spreadsheet YOUNG.XLS and the text file YOUNG.TXT.
5. **Initial conditions** must be provided for each constituent to be simulated (not bypassed). The initial conditions are usually only important until the system has had time to flush, so are important only for systems with long retention times.
 - c. **Constant lateral inflow concentrations** are also defined under the cross-sections. Since there were not constant lateral inflows, the associated inflow concentrations can remain zero (the default value).

9.4.2.3. SELECTING/CREATING THE AUXILIARY FILES

During the course of preparing input files, it is necessary to create, or select, the auxiliary files associated with the run. For this example, the following files were created with the Deliberator:

- Boundary Condition File,
- Lateral Inflow File,
- Withdrawal File, and
- Meteorological Data File.

In addition, a file was created externally to the pre-processor for this example containing the cross-sectional geometric data. To include these files in the Project, the user would select setup from the pick-list in the Auxiliary File menu or from the Toolbar icon and then select the appropriate files. They can then edit and evaluate the model input.

- 1) **Boundary Condition File:** this file can now be reviewed to ensure that it is correct. For this application, the same file was used by both the hydrodynamic and quality model, as would typically be the case. The user could select the file and then review it. A generic descriptive title was created by the Deliberator, which should be replaced by a more meaningful title by the user at this point. The user should then review the data to ensure that they are correct. If the user wishes to change units, or globally correct the values, they may use the scale and conversion factors. The values used by the model will be those estimated at a particular time (using either the stair-stepped or interpolated values) multiplied by these tow coefficients.
- 2) **Lateral Inflow File.** this file can now be reviewed to ensure that it is correct. The user should select the file and then review it. The generic descriptive created by the Deliberator should be replaced by a more meaningful title. If the node numbers are not correct, they may be changed at this point. The user should then review the data for each node that receives a lateral inflow to ensure that they are correct. If the user wishes to change units, or globally correct the values, they may use the scale and conversion factors provided for each node. The values used by the model will be those estimated at a particular time (using either the stair-stepped or interpolated values) multiplied by these tow coefficients.
- 3) **Withdrawal File:** the user should similarly review and edit, as necessary, the withdrawal file.
- 4) **Meteorological File:** the meteorological data file should also be review and edited. When this file was created by the Deliberator, it was not possible to enter certain information, and that information must be added at this point. The include:
 - 5) The node from which and to which the meteorological data apply. For this applicable, since only one file is used, the beginning node will be one and the final node 18.
 - 6) The dust attenuation coefficient (0.12 for this example)

- 7) Latitude (31.40 degrees),
 - 8) Longitude (85.10 degrees), and
 - 9) Longitude of the standard meridian (75.00 degrees).
- 10) Cross-Sectional Geometry File:** The cross-sectional files for this example were developed from field survey records. However, in the field survey, the over bank areas were not included. The banks of the river were relatively steep, and were not expected to be over-topped for the flows used in this analysis. For simplicity, A 2:1 side slope was assumed and the cross-sections extended to provide a much greater total depth than would be expected in the application. The input format for EPD-RIV1 consist of a series of X-Y pairs, where the X is the distance from the bank and Y the vertical distance downward to the channel bottom. An input file was created using these data (YOUGH.XSG), and can be reviewed in the model post-processor.

Once the two main input data sets have been prepared (for hydrodynamics and water quality), and the auxiliary files created or edited, then **the final step of preparing the initial model input is saving the project file.**

9.5. MODEL CALIBRATION

The model calibration analysis consists of the evaluation of the model input and determination of site-specific values of coefficients (e.g. roughness coefficients, kinetic coefficients). The determination of the site-specific values can only be determined through comparisons of model predictions with observed data.

The data for model calibration were also included in the project database for comparison with model predictions. The observed data consisted of:

- Daily stage measurements and weekly quality measurements at the Cassel Gage (Station ID CASSEL GAGE).

- Hourly water temperatures and dissolved oxygen concentrations and weekly measurements of concentrations of BOD (ultimate), ammonia-nitrogen, nitrate-nitrogen, ortho-phosphorus, and coliform bacteria at the Coleman Water Treatment Plant (station ID COLEMAN WTP).
- Daily flows at the Coleman Gage (Station ID COLEMAN GAGE).

The above data are included in the database file prepared for this example (YOUUG.DB). The measured flows at the end of the reach can provide a check of the water balance. The hydrodynamic model set up can also be tested against conservative tracer predictions. Slugs of a conservative tracer can be simulated to ensure that the predicted travel times are reasonable. The predictions can also provide a check to make sure that the model is numerically stable and phase errors are minimal. The observed data can be compared to model predictions, and coefficients adjusted until the best fit is obtained. Since model calibration is an iterative and time-consuming process, the steps are not repeated here. Instead, a final input data set is provided which agrees reasonably closely to the observed data. The user should attempt to calibrate the model and determine difference in their calibrated input data set and that provided.

9.6. MODEL PROJECTIONS

The final step in using this model is applying it for its intended purpose. The user should evaluate model predictions in comparison to standards and determine what, if any, load reductions would be required to bring the predicted quality concentrations into compliance. In addition, a proposed change in use allocation would result in a 20 percent average reduction in the flows from the Youg Dam. A model of the upstream reservoir may be used to estimate changes in release concentrations due to the changes in storage and the release schedule. However, an initial assessment may be made assuming the concentrations do not change and reducing the flows to provide an initial estimate of the impact of the change on downstream quality.