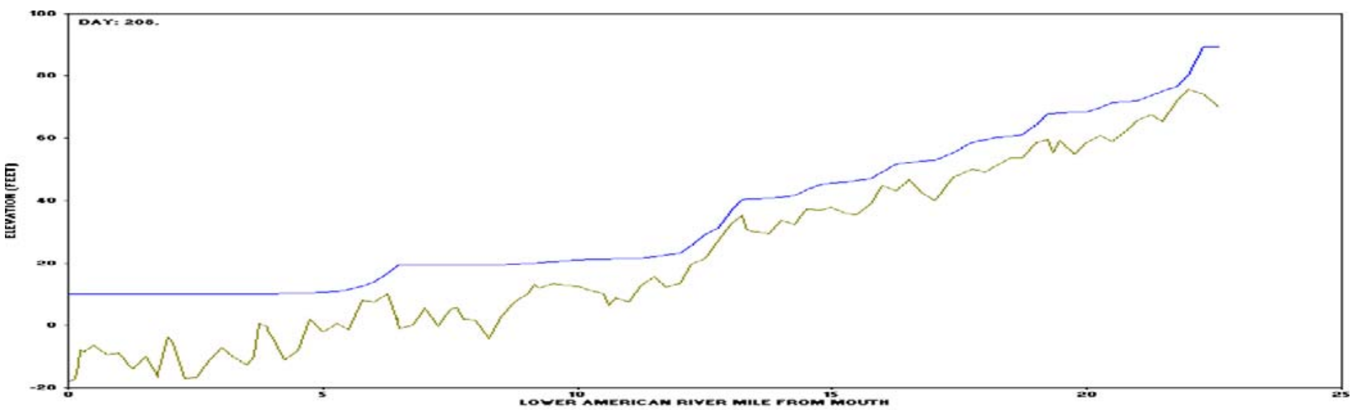
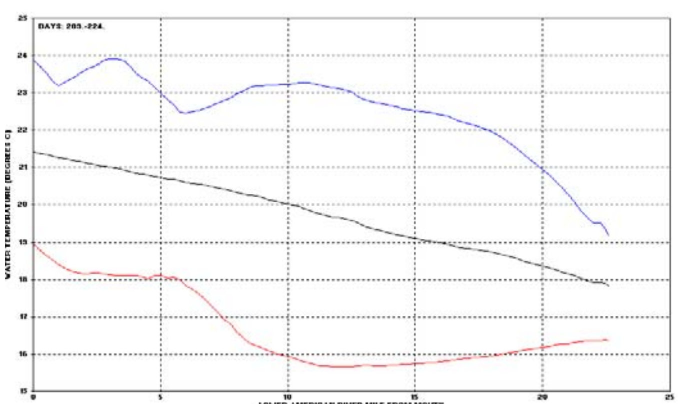
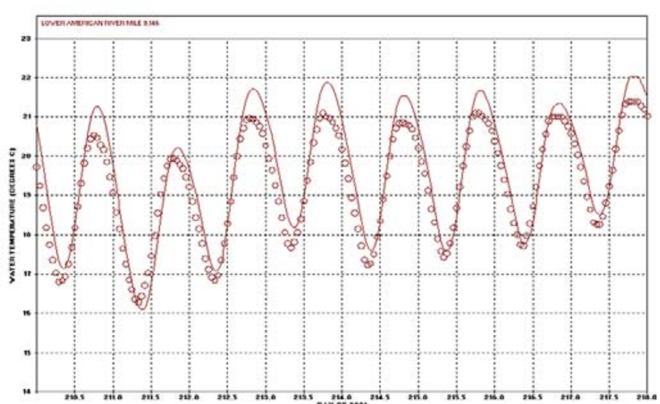
RECLAMATION
Managing Water in the West

Guidelines for Collecting Data to Support Riverine Hydrodynamic and Water Quality Simulation Models







U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

August 2010

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Executive Summary

Riverine models are extremely useful tools for exploring water quality downstream of dams and other shallow water environments. There are several types of riverine models and each requires a unique set of inputs that are specific to the model. Much of riverine modeling success can be tied to the selection of the riverine model, the layout of the river segments, and the riverine Sampling Analysis Plan (SAP), which describes the type of data, as well as when, where, and how often data are collected. Riverine water quality model calibration has more to do with adequate geometry to define riffle-pool relationships tied to water travel time than model calibration-coefficient adjustments. In regards to riverine modeling, selecting a riverine model, developing SAPs, collecting accurate and useful data, calibrating the model, assessing a target location, and writing the report can often be done more cost effectively than reservoir modeling. If a way to define riffle-pool geometry for determining water travel time is available, even cursory uncalibrated riverine models can be quite useful.

The primary goal of riverine flow and water quality modeling is to adequately express the water travel time that affects temperature and dissolved oxygen. Most of the water travel time exists in the deeper pools. Dye travel time studies at low flows are often necessary to calibrate riverine water quality models.

The many details of the various types of riverine models cannot be covered in a single document. These guidelines provide some important data collection tips for the decoupled flow and water quality completely-mixed fully-hydrodynamic model, ADYN/RQUAL. ADYN is the flow model and RQUAL is the related water quality model. In such decoupled models, the flow model and hydraulics can be calibrated before venturing on to the temperature and water quality model calibration. A reduced set of flow model simulations can be done before and separately from the overhead of the many water quality model simulations due to multiple water quality parameters. The following recommendations provide direction for dam tailwater and riverine modeling.

Six Data Collection Recommendations for Riverine Flow and Water Quality Modeling

There are six important input data recommendations for modeling water temperature, organic matter decomposition, and dissolved oxygen (DO) in completely mixed rivers and dam tailwaters. These are discussed below.

Choose a Model and Sampling Protocol

Choose a model first. Then choose the sampling protocol for that model and model construct (such as the number of river reaches, bridge locations, longitudinal segment size, and tributary inputs to model segments). Many fully hydrodynamic models become unstable with large flow fluctuations on lateral inflows. Therefore, when there is a major hydropower discharge into a channel that then discharges into a main channel, it is often useful and appropriate for modeling stability to consider the discharge channel as part of the main modeled channel, and to represent the main river channel above the confluence as a tributary or dynamic tributary in the model. Starting the modeled main channel at a dam, even if the dam is not on the main river channel, may prevent numerical instabilities during simulations that stretch the model outside the range of conditions to which the model was calibrated. Weirs in the main channel may need to be modeled as internal boundary conditions in which flow over the structure is a function of time or hydraulic head model inputs. Model construct and effects on numerical instabilities should be carefully considered before data collection.

Choosing a model before collecting data allows for collection of the type of information required by the model in the desired locations. Sometimes, a model cannot be used for a particular application. For example, a steep river at low flow that results in a near hydraulic jump (whitewater) may cause a fully hydrodynamic model to stop during numerical simulation. Resulting adjustments could be made to the model construct such as a deep low volume cut (deep and thin V–shaped sliver in the channel bed referred to as a Preissman slot) to allow the model to continue running and calculating expected hydraulics without significant change in overall volume and results. It may be necessary to model waterfalls, weirs, and steep reaches as multiple internal boundary conditions. Alternately, another model that is not fully hydrodynamic, such as WASP, could be chosen for steep mountainous regions or if rating data are not available for internal boundary conditions. The chosen model and model construct both should be used to guide the data collection locations if enough cursory data are available to construct a screening test model. In some cases, the chosen model might need to be discarded for a model that handles the specific conditions being modeled in a different manner.

Collect Riffle-Pool Cross-Sectional Channel Geometry

The most important parameter for riverine water quality models used to simulate riverine flow and temperature is cross-sectional channel geometry that adequately captures water travel time in pools and riffles and is tied to a known vertical datum. About four to five cross sections per river mile will be required to capture riffle pool sequences. Most cross sections will be taken to define pool volume. Few cross sections are needed in riffle areas containing minimal volume. However, a longitudinal thalweg profile of the deepest pool bottom locations and riffle tops of the river channel may need to be surveyed before selecting where cross sections are to be taken to define slope changes as well as volume of pools.

Collect prior data at upstream boundary condition

Upstream boundary conditions are extremely important to riverine modeling; therefore, it is important to select upstream branch locations where data is collected such as at a dam or gage. Often the first hours or days of riverine model results are discarded due to unknown water surface elevations along the modeled reaches and discharge of unknown boundary conditions (such as unmeasured tributary inflows). Therefore initial condition and upstream boundary condition data should be collected prior to the desired model simulation start time to "damp out or wash out" initial conditions that are set or estimated without data such as at downstream river model locations or ungaged tributary inflows. A primary concept of riverine modeling is to reproduce the water travel time and the effects on a drop of water as it moves through the riverine reaches. Some flow model algorithms, such as ADYN's Lagragian particle tracker, calculate water travel time of a drop of water through the model reaches allowing comparison to dye travel time studies. Model results from the first time period, during which a drop of water travels the riverine reaches, should be discarded to damp out estimated initial conditions. Diurnal events, such as daily heating and cooling, tend to dominate riverine models. Important processes, such as morning fog or shading which cuts off solar radiation, might need to be factored into riverine model data collection plans. Data collection needs to be planned around when the desired model results will be considered free of initial condition effects.

Collect near-continuous diel temperature and water quality data

Day and night temperature and dissolved oxygen swings coupled with changes in flow and water quality conditions over time affect the longitudinal water quality profile of a river. Temperatures rise and fall in a whip-like fashion along the river. For example, there is an offset between air and water temperature fluctuations. Fluctuating model inputs are difficult to derive without near-continuous data. Continuous temperature recorders are inexpensive and can be hidden in the river to continuously record water temperature. Dissolved oxygen will likely need a synoptic survey done over about a week to provide adequate model inputs and calibration data.

Collect travel time (dye study) data while collecting calibration data

At least one dye study should be done during known low-flow conditions to calibrate a riverine flow model. Rhodomine WT dye (red) or fluorine (yellow) florescent dye can be read with a fluorometer. Red dye in the river can alert the public and therefore yellow dye is typically used if the water travel time dye study cannot be done at night. Dye studies mimic the tracking of a particle of water downstream and therefore are a good indication of water travel time. Typically other model input data, such as flow, temperatures, and meteorology are also collected at the time of the dye study for model calibration. Low-flow calibration data sets are preferred for water quality model calibration.

Collect completely-mixed integrated samples and avoid eddies

A common mistake is to place a gage or collect samples near the riverbank in a recirculation eddy, backwater area, or in a location where solar radiation directly shines on a thermistor. Samples that are representative of a completely-mixed condition should be collected. If stratification occurs in pools, a different model may need to be selected or the riverine model divided into reaches with internal boundary condition inputs. Sometimes moving a model calibration station upstream or downstream greatly improves model calibration. A sample collected in a pool will not mimic one collected on a riffle. The field sampling location does not need to be changed or moved. Select a different model location to match the pool or riffle condition in the reach by adding interpolated nodes. Access issues in the field may limit the collection sites available. However, any reach of the model can be analyzed without changing field sampling protocol or locations. Figure 1 shows a modeled riffle location that heats up more than seen in the field while tracking the daily heating pattern swings. Both modeled and measured information in figure 1 may be correct and the field sampling location slightly different. Or the model calibration could be too warm during daylight hours.

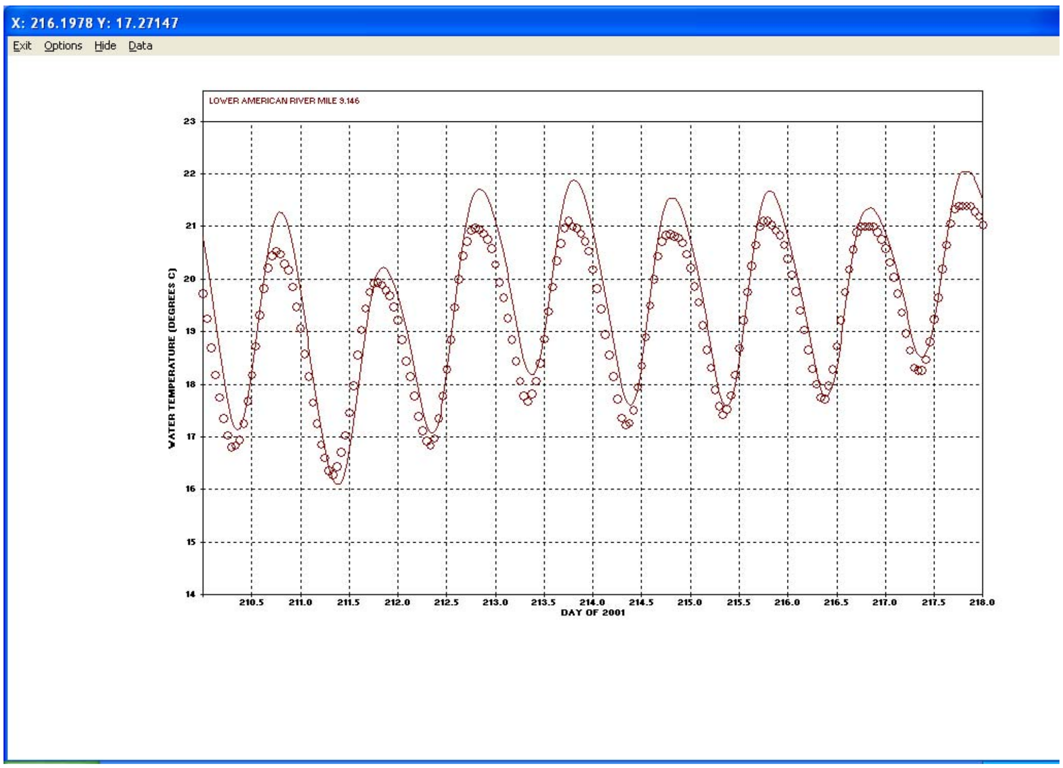

Figure 1.—Example of closeness-of-fit between model (line) and observed (circles) daily water temperature data at one riverine location (from Bender et al, 2007).

What is Covered in These Guidelines?

The following guidelines were written with an emphasis on water quality data collection and one-dimensional (1D) modeling of rivers and tailwaters downstream of dams. Some of those models are described in Appendix A. Novotny, el al. reviewed common ecological models (2006) and other literature reviews provide similar comparisons. Data collected for reservoir models differ and are covered in a separate document (Reclamation, 2009). Reservoir models often provide the upstream boundary condition for dam tailwater riverine models. Therefore, information on selective withdrawal from a reservoir is also included in this document.

Several types of data are required for riverine modeling including: Model geometry (bathymetry developed from either cross-sectional channel geometry (Appendix B) or x,y,z survey data), measured initial conditions throughout the modeled reaches (if not damped out), inflow water quality at the mouth of major inflows (including local inflows) of major tributaries, water quality over time at riverine locations (typically at bridges or readily accessible sampling locations), branch and tributary inflows above the confluence, dam outflows and other withdrawals, dam release temperature and water quality, and meteorological data.

In this document, riverine simulation modeling is described for a decoupled flow and water quality temperature and DO model calibration. Cross-sectional channel geometry that captures the riffle-pool sequence is required to build the numerical three-dimensional container for the model. Flows in and out of the river reaches are needed for water mass balance calibrated to water surface elevations, wave travel time, stage data, water travel time, and the timing of water temperature and dissolved oxygen dynamics. Reservoir release data are required for modeling flow and water quality of a tailwater. Hourly or smaller-timestep meteorological data are required to replicate diurnal patterns. Water quality data are then added to the model to simulate algal growth and assimilative capacity of organic matter degradation. A typical case reflecting organic decay is sagging DO concentrations downstream of a wastewater treatment plant outfall that discharges into the river.

Unfortunately, data collection efforts in support of modeling are often not completed and are many times abandoned due to economic constraints. Therefore, data collection priorities and practical considerations are covered in these guidelines to maximize data collection activities in support of riverine model calibration. A few model calibration data sets, in combination with sensitivity analysis, often provide great insight into the water quality conditions of river reaches and how to alter operations for release water quality improvements or assimilative capacity of the river.

Guidelines for Collecting Data to Support Riverine Hydrodynamic and Water Quality Simulation Models

Application

Well-calibrated numeric riverine dynamic flow and water quality models are useful tools for predicting and evaluating the implications of structural or operational alternatives before undertaking these expensive modifications. Model results depend on the underlying input data to produce a computational river reach network that accurately represents the riffle and pool characteristics. To capture varying water quality from low flow to high flow conditions, riverine water quality data for modeling require planning and data collection several months in advance.

The primary application of the following guidelines is for data collection supporting the ADYN/RQUAL riverine model or a similar fully hydrodynamic, 1D, completely-mixed riverine water quality model. ADYN/RQUAL is a decoupled flow and water quality model that allows optimizing flow and hydraulics separately from the water quality model and produces a hydraulics model output for use with multiple water quality modeling scenarios. Appropriate planning for environmental data collection and processing is critical to overall success in developing accurate predictive simulation capability.

Purpose and Scope of Guidelines

These guidelines address critical data necessary to support ADYN/RQUAL, a widely recognized and well-proven numeric 1D river flow and water quality simulation modeling technology. The focus is on data sources, priorities for data collection, and practical considerations for compiling and processing data to develop effective modeling capabilities. These guidelines do not replace detailed ADYN/RQUAL modeling theory or technical instructions, such as those provided by Hauser and Schohl (2002). These guidelines are intended to provide insight into factors involved in data collection for riverine tailwaters downstream of a dam for typical Bureau of Reclamation (Reclamation) riverine modeling applications and water resource planning investigations. However, the data could be used to support other models.

These guidelines can provide insight to help prioritize types of data and how the data need to be collected at a regional planning level. Data collection for a specific project would need to be captured in a SAP tailored for the project. A SAP answers questions such as what, where, when, how, with what equipment, to what standards and quality assurance/quality control (QA/QC), and who is responsible for collecting the flow, sediment, and water quality data. Sampling protocols, field and laboratory QA/QC, analytical methods, data processing, and data storage issues are addressed in “Quality Assurance Guidelines for Environmental Measurement” (Bureau of Reclamation, 2002 revised August 2003). The “Quality Assurance Guidelines for Environmental Measurements” provide templates in many areas of the planning and data collection process. The “Technical Guidelines for Water Quality Investigation” (Bureau of Reclamation, September 2003) cover additional technical details, approaches, and general information for planning water quality investigations.

Many questions need to be answered before going in the field to collect riverine data including:

- Where are the representative sample locations along the river reaches?
- Instrument calibrations or sample bottle holding times?
- Synoptic sampling during a few days or long term sampling over months?
- Duplicates, blanks, rinsate blanks, replicates, splits, spikes, lab round-robins, and references?
- Half meter, one meter, five feet, pool bottom, surface, grabs, integrated composites or continuous sampling?
- Monthly, bi-weekly, weekly, daily, hourly, continuous, or telemetered data?
- U.S. Geological Survey (USGS), Environmental Protection Agency (EPA), or Standard Method (American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF), 2005) protocols and procedures?
- Meta-data, recording procedures, and chain-of-custody?

Other considerations include:

- Sampling to accommodate laboratory analysis procedures
- Job Hazard Analysis
- Data processing
- Archival of data for future projects
- Model calibration
- “Honoring” the data and initial data analysis before simulating future conditions and writing a modeling report.
- Project oversight and peer review

- Planning for future automated data collection and telemetry to a riverine and reservoir operations center

- Selective data archival for future trend analysis

Collecting environmental data is not a simple process and requires adequate planning.

Role of Riverine Simulation Models in Water Resources Planning

Riverine water quality and hydrodynamic modeling capabilities, such as calibration to high flow, low flow, and a flow pulse for simulating (computing) over a range of conditions, are developed using measured input data that reflect defined (historic) dynamic conditions. The model uses these data sets to accurately simulate processes governing hydrodynamic and water quality conditions in the riverine environments.

Model input data must be collected in advance to accurately represent the actual conditions of interest. For example, to accurately predict how structural or operational modifications would influence riverine conditions during low flows, model calibration should incorporate data collected during low flow conditions.

The resulting modeling capabilities provide a long-standing resource that can extend the scope and accuracy of water management investigations. Current state-of- the-art riverine models can accurately represent a range of hydrodynamic and water quality processes. For example, a competent simulation model, such as ADYN/RQUAL, could help predict the dynamic effects of operational or structural changes on thermal heating or effective duration and degree of influence on the downstream river reach.

Simulation models are used to provide critical planning information for decisions and testing of alternatives before design costs are incurred. If applied properly, models are valuable tools for managing water resources. However, if data supporting the models are lacking, inaccurate information may be produced from the modeling effort.

On the other hand, a preliminary screening or test model based on the best available historical data is a valuable tool for SAP design. Coarse, uncalibrated models, or other types of models already applied to the system, are used to determine data requirements for a more calibrated model or to determine what major forcing functions and input variables are most important for a particular river. The best way to ensure accurate and complete modeling data sets is to run a coarse model to guide the data collection planning process for a future one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D) modeling effort, depending on the application scenario.

A system-wide approach to data collection must be kept in mind because data collected will be used in other models in future studies. Table 1 lists some typical water quality models that might be used to answer different questions. There are thousands of models, and table 1 lists a short sampling of the available models, many of which contain a riverine routing model. Appendix A further describes some of the models listed in Table 1.

Riverine Simulation Modeling

There are frequent misunderstandings concerning the appropriate application and value of numeric simulation models. Simulation models are mechanistic, are often tailored to a specific riverine environment, and are developed using actual data and projected operational information. The term “model” itself is generic and can encompass a wide scope ranging from simple empirical equations to highly complex computer simulation systems. It has been said that all models are wrong, and some are useful. That statement likely came about because not all complex processes, especially biological processes, can be modeled entirely, due to lack of data and understanding of complex environmental processes. However, if required modeling data is collected correctly, and if a competent hydrodynamic and water quality model is calibrated to a wide range of hourly conditions, such a previously tested and trusted model becomes extremely useful and a valuable water resource management tool. Even uncalibrated models are useful for cursory sensitivity analysis to investigate large differences between input scenarios.

Riverine models are constructed from available data representing the physical configuration and measured data sets that represent transient operational, hydraulic, meteorological, and water quality conditions. Model data sets and simulation processes are tied to a specified time step. For example, tailwaters with peaking-power operations require at least an hourly time step. As a result, the many interrelated factors involved in a typical model construct can make it difficult to review an existing model and isolate data factors from the original model development. In addition, future development could be based on refining an existing model or improving existing model data sets, rather than assembling an entirely new model.

Different Types of Riverine Models

The three basic questions that need to be addressed before selecting a model and collecting data are: (1) What questions need to be answered? (2) In what detail? and (3) How do the results need to be presented technically and politically? Model selection typically depends on the time and funding available for collecting data, for calibrating to a range of hydrologic conditions, for running simulations, and for preparing and presenting results. Modeling is costly and often takes years. However, a reasonable amount of data with model simulations can provide valuable information.

Table 1.—Dynamic riverine water quality models

Model name/acronym	Short description	Scale
ADYN-RQUAL	Unsteady state decoupled flow and water quality model for use in low-flow rivers (river modeling system (RMS))	Riverine
AQUATOX	Fugacity model to predict fate of toxics, nutrients, and chemicals in the environment and resident organisms	Water bodies
EPD-RIV1	Decoupled flow model for use with EPDRiv1Q or WASP water quality models.	Riverine
EFDC	Computational fluid dynamics code for one, two, and three dimensional problems and provides WASP input.	Water bodies
MIKE11	Flow, water quality, and sediment transport flood plain model with external links to groundwater models	Riverine
RMA11	Finite element hydrodynamic and water quality model for use in estuaries, bays, lakes, and rivers	Riverine
CE-QUAL-RIV1	One-dimensional decoupled hydrodynamic (RIV1H) and water quality (RIV1Q) model	Riverine
Columbia R. Temp Model	EPA's (Yearsley's) steady flow model for daily averages over multiple year scenarios	Riverine systems
DSSAMt	Dynamic water quality on weekly flow time step for modeling yearly riverine water quality simulations	Riverine
CE-QUAL-W2	U.S. Army Corps of Engineers water quality 2D model for reservoirs and deep rivers	Reservoir Riverine
Heat Source	Riverine model that simulates thermodynamics with varying vegetative canopy	Riverine
HEC-HMS	HEC-Hydrologic Modeling System—unsteady state flow model for watersheds and rivers	Watershed Riverine
HEC-RAS	HEC-River Analysis System—steady state flow model for use in rivers (no water quality)	Riverine
HSPF	Hydrological Simulation Program—FORTRAN, data intensive hourly input water quality program	Riverine Watershed
HYDROSS/CRRSAP	Hydrologic and water quality mass-budget accounting model for use in modeling large river systems	Riverine
MINTEQA2	Calculates equilibrium chemical balance in water systems	Riverine Reservoir
PHREEQE	pH-Redox Equilibrium Model—reaction can be maintained in equilibrium or used to evaluate changes during transport	Any water
QUAL2EU or Q2K	Enhanced stream water quality model with uncertainty analysis for well-mixed streams (QUAL2K—with rates)	Riverine
RIVERWARE	System-wide operational model	System
SNTEMP	Stream Network Temperature Model for daily mean and maximum water temperatures shade model	Riverine
WASP7	Hydrodynamic river water quality model—eutrophication, metals, and toxics (version 7.41)	Riverine
WARMF	Watershed Analysis Risk Management Framework—stakeholder daily watershed planning model	Watershed

Different types of models are designed to serve different purposes. For example, 1D riverine models (completely mixed) are limited for braided streams and for wide rivers with lateral gradients. By contrast, 1D models that do not allow fully hydrodynamic simulation may accommodate such limiting conditions. However such models are extremely limited for varying flows and are often not appropriate for unsteady flow conditions.

The basic model framework is adapted to specific conditions, and data sets are compiled, analyzed, and assembled as appropriate to accurately represent the major mechanisms in play. This factor alone causes some difficulty and uncertainty in understanding an existing underlying model construct well enough to make adaptations. Applying an existing model directly, without significant analysis of what went into the original model calibration, may result in misuse or misinterpretation. To overcome these uncertainties, a stepwise hierarchical model approach or decision plan is often more cost effective and practical to guide model application efforts.

Using a simpler 1D model versus increasing data and computation requirements is a compromise. A well-defined, fully-calibrated 1D model, such as ADYN/RQUAL, can provide a cost-effective means to simulate hourly, daily, and seasonal operational conditions in a dam tailwater or to investigate structural features in that tailwater while addressing interrelated water management questions including habitat for aquatic biota, support for Instream Flow Incremental Methodology (IFIM) studies, and bioenergetics studies that require flow, backwater, depth, wetted area, and other hydraulics information. The decoupled RMS model has a hydrodynamic module called ADYN, a water quality module called RQUAL, a fish growth (bioenergetics) module called FISH, and a habitat module called RHAB that is supported by a cell velocity model called CELVEL. A contaminant transport component is also in development.

The thoroughly tested 1D ADYN/RQUAL model is an array of hydraulic transport, heat transfer, and chemical transformation algorithms and coefficients to fully support hydrodynamic simulations of water quality conditions in many completely-mixed rivers. Version 4 of the River Modeling System (RMS) model (Hauser and Schohl, 2002) has been upgraded extensively. Recent versions of RMS have an upgraded pre-processor and post-processor to accommodate changing user needs. Extensive use of RMS generated riverine animations over a reach through time is possible through the Animator Graphics Portfolio Manager (AGPM) for presenting a single day in combination with 1D whip-like animations during the calibration process. Error checking, statistics for calibration, enhanced plotting, and many other features save modelers effort and time calibrating, preparing, and presenting information. For example, a week of temperatures at a location versus time and typically plotted at the inflow, at mid-river, and at the lower exit from the river, can provide a weekly picture of the entire river for observed or modeled data. A whip-like 1D animation of the constituent, such as temperature, versus river mile simulated over time can provide a moving snapshot of all river locations in a reach. Additionally, plots through time of several hydraulic parameters at several locations provide a powerful learning tool for quickly analyzing extensive data sets of riverine water quality or thermal characteristics.

The ADYN/RQUAL model is a fully hydrodynamic model which uses the equations of mass and momentum to calculate hydraulics. Inflows and outflows affect the wave of water flowing downstream and are used to calculate backwater effects. ADYN/RQUAL model geometry consists of widths, lengths, and varying Manning n (friction) of each river reach stream channel. Each cell's water volume is calculated every iteration. RMS Version 4 (Hauser, G.E, and J. Schohl, 2002) and newer versions include the following modules:

- Hydrodynamics (ADYN) with plot package ADYNEXT
- Water Quality (RQUAL) with plot package RQEXT
- Bioenergetics fish growth (FISH)
- Physical habitat (RHAB) for support of IFIM studies
- Cell velocity model (CELVEL) for RHAB
- Contaminant Transport (in development and previous specialized versions used to model spills)

The hydrodynamics (ADYN) model includes the following features:

- Dynamic junctions for branching models
- Variable grid spacing and river lengths
- Time varying conditions over small timesteps
- Internal boundary conditions for weirs and steep reaches
- Backwater initial conditions generator
- Statistics built into ADYNEXT plot package
- Hydrodynamic output processing with statistics and plotting

The water quality model (RQUAL) model includes the following features:

- Dynamic junctions
- Time varying conditions matching a multiplier of the hydrodynamic timestep
- Tributary boundary conditions

- Riparian and/or topographic shading
- Statistics built into RQEXT plot package
- Water quality output processing with statistics and plotting

Recent versions of RMS have been tested extensively and have few coding bugs. Version 4.2 has enough functionality for most applications. In addition, the RMS users manual (Hauser, G. E and Schohl, J., 2002 (revised draft 2003)) describes a number of other useful enhancements and improvements to the model computational methods. This documentation explains major model limitations and considerations for appropriate application to different types of riverine conditions. The more recently released and more feature-laden versions are in beta testing. Newer, less-tested versions of RMS have more capability, are still being debugged, should be used with caution, and should be thoroughly calibrated over a range of hydrologic conditions to improve confidence.

Coupled with auxiliary tools and off-the-shelf pre-processors and post-processors for plotting and animating, the utility and capability of the RMS model to predict hydrodynamic, thermal, and water quality changes has allowed it to become a favorite tool for modeling unsteady flow and water quality of tailwaters downstream of dams. There are more complicated models available that can cover a wider range of issues. Due to its hydrodynamic abilities and simplicity, RMS has been used in place of 1D models such as the QUAL2K model (http://www.coe.uncc.edu/~jdbowen/6141/QUAL2K/Q2KDocumentation.pdf) or the WASP model (EPA, http://www.epa.gov/athens/wwqtsc/html/wasp.html) version 7.41 (release date June 7, 2010) . WASP model version 6 documentation is available. The ADYN/RQUAL model, coupled with innovative approaches to capturing 1D animations, has been successful at cost effectively modeling numerous scenarios such as heating of dam releases over a downstream reach or dissolved oxygen sags (and swings) downstream of a wastewater treatment plant.

The RMS modules of the ADYN/RQUAL model are described in more detail in the following sections.

ADYN (hydrodynamic module)

ADYN solves the one-dimensional, longitudinal equations for conservation of mass and momentum (St. Venant equations) using a four-point implicit finite difference scheme with weighted spatial derivatives. Major model inputs include channel geometry, roughness coefficients, upstream and lateral inflows, boundary rating curves, and initial water surface elevations and discharges throughout the modeled reach.

ADYN is used to study unsteady river and reservoir hydraulics where the following are of interest:

- Water (particle) or wave (front) travel times

- Routing of natural or manmade flow waves
- Dynamic effects of transient hydropower releases
- Effects of hydraulic structures at downstream or internal boundaries
- Effects of distributed or point lateral inflows
- Effects of channel shape and roughness on flow waves, depths, velocities and wetted areas
- Flow reversals
- River systems with multiple tributaries and dynamic junctions
- Hydraulic interactions between main channel and tributaries at channel junctions
- Multiple reaches each with multiple internal boundary conditions and inflows
- Flow and elevation hydrographs at locations between stream gage sites
- Effects of channel geometry and roughness on flow and water surface elevation

Various graphic display options are available using the legacy ADYNEXT (early version of ADPLT) post-processor program to display ADYN output and statistics. Plotting and statistical options show the strengths and capability of the fully hydrodynamic ADYN model. Plotting of both model and field data are possible for some options.

Some of the plot options for reporting ADYN output include the following:

- Flow versus time for any node (including interpolated) location (Q vs T)
- Water surface elevation versus time for any node location (H vs T) including cross-section bottom, average depth, and water surface elevation profiles
- Flow versus river mile (Q vs MI)
- Water surface elevation versus river mile (H vs MI)
- Water surface elevation versus flow at any node location (H vs Q)
- Cross section bottom elevations versus distance from bank (ELEV X-XSECS)
- Volume versus time for any subreach (VOL vs T)

- Velocity or Froude number versus time for any subreach (V,FR vs T)
- Velocity or Froude numbers versus river mile for a snapshot in time (V, FR vs MI)
- Water travel time for any subreach (TF vs T)
- Courant Condition for entire reach (DX/DT vs MI)
- Channel friction (Mannings n) versus mile for a reach (N (MIN) vs MI))
- Surface area versus time for any subreach (ASUR vs T)
- Surface area versus flow for any subreach (ASUR vs Q)
- Lagragian particle tracking from any node (MI vs T-TRACK)
- Wetted surface width versus river mile (WSUR vs MI)
- Mean water depth versus river mile (DMEAN vs MI)
- Mean water depth versus time for a subreach (DMEAN vs T)
- Minimum, mean, and maximum flow, water surface elevation, velocity, or mean depth versus river mile (MAXMIN vs MI)
- Velocity versus mean depth for a subreach (V vs DMEAN)
- Mean depth versus time (DMEAN vs T)
- XYZ output for 3D channel topography plotting
- XYZ output for 3D model results plotting
- Flow versus percent of time (Q vs %TIME) or flow duration at a node
- Water surface elevation versus percent of time (H vs %TIME) or elevation duration
- Cumulative flow versus time at any node (cum Q vs T)

Mnemonic definitions:

A	cross sectional area of flow (ft^2)
AMSL	above mean sea level (ft)
ASUR	water surface area for a reach (ft^2)

DMEAN	mean depth of water (A/WSUR in ft)
DX/DT	distance step/time step (ft/s)
EL	elevation (ft AMSL)
FR	Froude number (dimensionless ratio of inertia to fluid weight)
H	water surface elevation (ft AMSL)
MAXMIN	max-mean-min of Q, H, V, or DMEAN (cfs, ft, ft/s, ft)
MI	river mile
N (MIN)	main channel roughness coefficient (Manning's n)
Q	volumetric river flow rate (cfs)
T	time since start of simulation (hours)
TF	instantaneous water travel time (DX/V in hours)
TRACK	tracking/backtracking of particle
V	water velocity (ft/s XSEC average)
VOL	water volume in river reach (1000 dsf)
WSUR	water surface width (ft)
X	transverse distance in channel (ft)
(XSECS)	cross sections

RQUAL (water quality module)

RQUAL is a river water quality model that solves the mass transport equation with a choice of two different numerical schemes (the 4-point implicit (shallow water) and the Holly-Priessmann (shallow or deep water) schemes). ADYN's McCormack explicit scheme for deep water scenarios is obsolete and has been discontinued (turned off in the compiled code) because it lacks functionality with dynamic tributaries. Major model inputs include meteorological data (air temperature, dewpoint temperature, wind speed, cloud cover, barometric pressure, and solar radiation), inflow quality from all inflow sources, and initial water quality throughout the modeled reach. RQUAL is used in conjunction with ADYN to study temperature, nitrogenous biochemical oxygen demand (NBOD), carbonaceous biochemical oxygen demand (CBOD), and dissolved oxygen (DO) in rivers where the one-dimensional longitudinal flow assumption is appropriate.

The following can be studied with the combined flow (ADYN) and water quality (RQUAL) model components:

- Waste load allocation
- Effects of location, magnitude, and timing of interventions to improve water quality
- Dilution and degradation of wastes
- Effects of thermal loadings and atmospheric heat exchange on stream temperature
- Effects of natural or artificial aeration, diurnal photosynthesis and respiration by macrophytes, waste loads, tributary inflows, and variable flow regimes on the DO regime
- Effects of weirs and other hydraulic structures

Graphic display options are available for plotting RQUAL model output and statistics using the legacy RQEXT (early version of RQPLT) post-processor.

Plotting and statistical options show the strengths and capability of the dynamic RQUAL model.

Some of the plot options for reporting RQUAL output include the following:

- Water temperature or stream bed temperature versus time (TEMP vs T)
- BOD versus time (BOD vs T)
- Dissolved oxygen versus time (DO vs T)
- Water temperature or stream bed temperature versus river mile (TEMP vs MI)
- BOD versus river mile (BOD vs MI)
- Dissolved oxygen versus river mile (DO vs MI)
- Percent of time that DO is greater than selected concentration versus mile (%Time DO > vs MI)
- DO Mass versus time (DO Mass vs T)
- DO Mass versus mile (DO Mass vs MI)
- Minimum, mean, and maximum flow, water surface elevation, velocity, or mean depth versus river mile (MAXMIN vs MI)

- Heat or DO process rates versus time
- Nitrogenous Biochemical Oxygen Demand versus time (NOD vs T)
- Nitrogenous Biochemical Oxygen Demand versus mile (NOD vs MI)
- Model coefficients versus mile
- Change in concentration over time (DC/DT versus rate analysis)

Mnemonic definitions:

BOD	Ultimate carbonaceous biochemical oxygen demand (mg/L)
DO	dissolved oxygen concentration (mg/L)
%time DO >	percent of time that DO levels exceed given DO values over a specified portion of the simulation
DO Mass	cumulative DO mass passing any location
MAXMIN	max-mean-minimums of temperature, TBED, DO, BOD or NOD over a specified portion of the simulation (°C or mg/L)
MI	River mile
NOD	Nitrogenous biochemical oxygen demand (mg/L)
T	time
TEMP	water temperature (°C)
TBED	channel or stream bed temperature (°C)

DO Process Rates are all modeled physical and biochemical processes that affect the DO levels, normalized by mean depth to units of $gO_2/m^2/day$.

Heat is all modeled processes that affect temperature in units of $kcal/m^2/hr$.

FISH (bioenergetics fish growth module)

FISH is a bioenergetics fish growth model that simulates growth of individual fish as a function of food availability, temperature, and dissolved oxygen. Using temperature and dissolved oxygen outputs from RQUAL and estimated or calibrated food availability, the model simulates energy exchanges from food consumption, assimilation, waste processes, metabolic expenditure, and growth for any fish species for which certain parameters are available or can be estimated. Major inputs to FISH include temperature and dissolved oxygen over time throughout the modeled tailwater from RQUAL, fish characteristics such as food consumption and respiration parameters, and food availability assumptions. The model can be used to:

- Explore relative benefits of temperature and dissolved oxygen release patterns, such as those that might be created by aeration, temperature control devices, or alternative operating policies at hydro plants that would influence temperature and dissolved oxygen.

- Explore how fish growth differs at different distances downstream from a dam or other source of impact.

Columnar output files of FISH results can be easily imported into spreadsheets for plotting.

RHAB (physical habitat module)

RHAB is a river physical habitat model that emulates the Physical Habitat Simulation System (PHABSIM) habitat calculation of weighted useable area (WUA), for unsteady flows and for entire river reaches or any subreach therein, meaning that RHAB calculates WUA(x,t). Both WUA and "high-value" WUA are calculated by RHAB, where high-value WUA includes only those cell areas with a combined suitability greater than a certain user-defined threshold. CELVEL calculates cell depths and cell velocities for RHAB based on ADYN input cross sections and roughness variations laterally across each cross-section (interpolated model nodes are excluded from the calculations) and ADYN output cross-sectional average velocities at each node and time. CELVEL can calculate average cell velocity over the cell depth, or it can calculate bottom velocities within a user-specified height off the channel bottom, for riffle dwelling species. Bottom velocities are calculated based on cell average velocities and a logarithmic velocity profile formulation. Major model inputs include the ADYN input geometry, and ADYN output hydrodynamics. ADYN provides velocities and cross-sections to CELVEL, which provides cell depths and velocities to RHAB. RHAB takes the cell depths and velocities from CELVEL, brings in substrate and cover field data if available, and reads in habitat suitability curves for various species and life stages, then computes WUA and high-value WUA for any reach or subreach in the model. All species in the suitability curve library are simulated. CELVEL and RHAB are used in conjunction with ADYN to study the following:

- Incremental changes in WUA(x,t) and high-value WUA(x,t) with discharge

- Changes in WUA(x,t) and high-value WUA(x,t) over time with varying upstream dam operations

- Amount of wetted area in various depth classes for a range of discharges

- Comparative effects of operations on habitats of different species and life stages

- Fraction of total wetted area that is useful
- Effects of various bottom habitat assumptions on WUA results. Columnar files of RHAB results can be easily imported into spreadsheets for plotting.

Major Physical and Biochemical Processes

Selection of either a 2D or 1D model depends primarily on reservoir stratification and longitudinal variations in water quality. Some of the major physical and biochemical processes modeled by reservoir models are shown in figures 2 and 3. Many of the two dimensional reservoir processes shown in these figures cannot and should not be modeled with a one-dimensional completely-mixed riverine model for any thermally stratified situations. A one-dimensional riverine model will not properly model interflows and shearing past embayments and should not be chosen for modeling stratified impoundments. Algal growth and algal mortality are simple formulations in most 1D water quality models. Some models, such as DSSAMt, simulate algae attached to bottom substrate and are referred to collectively as periphyton. Simulation of periphyton is important in clear western shallow streams where long strands of filamentous algae attach to rocks and strip the water column of nutrients. Scouring flows strip the attached algae from substrate and push decaying biomass and nutrients downstream in a process referred to as nutrient spiraling (Wetzel, 2001). Such dynamic processes are difficult to model without specialized modeling tools.

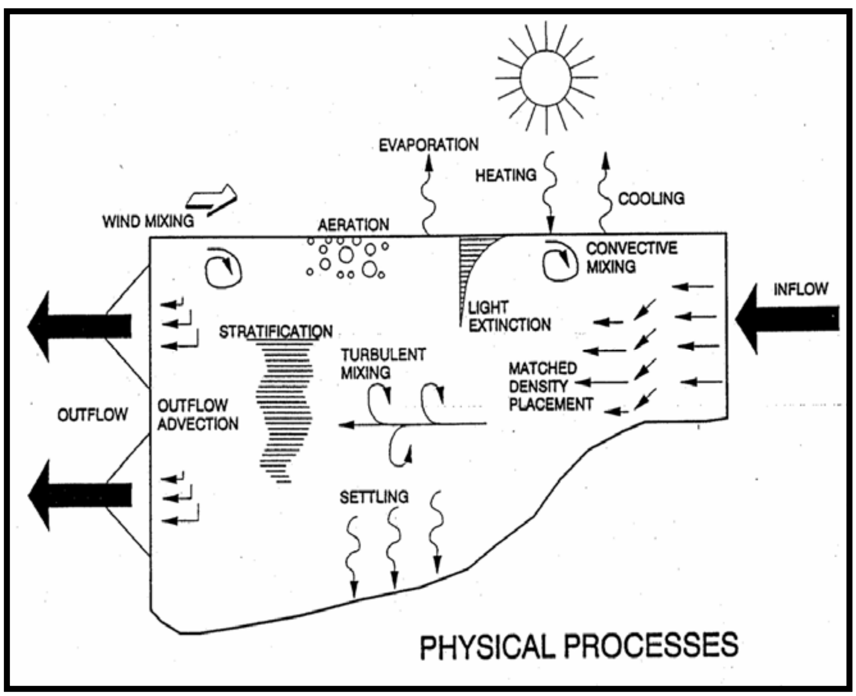

Figure 2.—Major physical processes modeled in reservoirs (Bender et al., 1990)

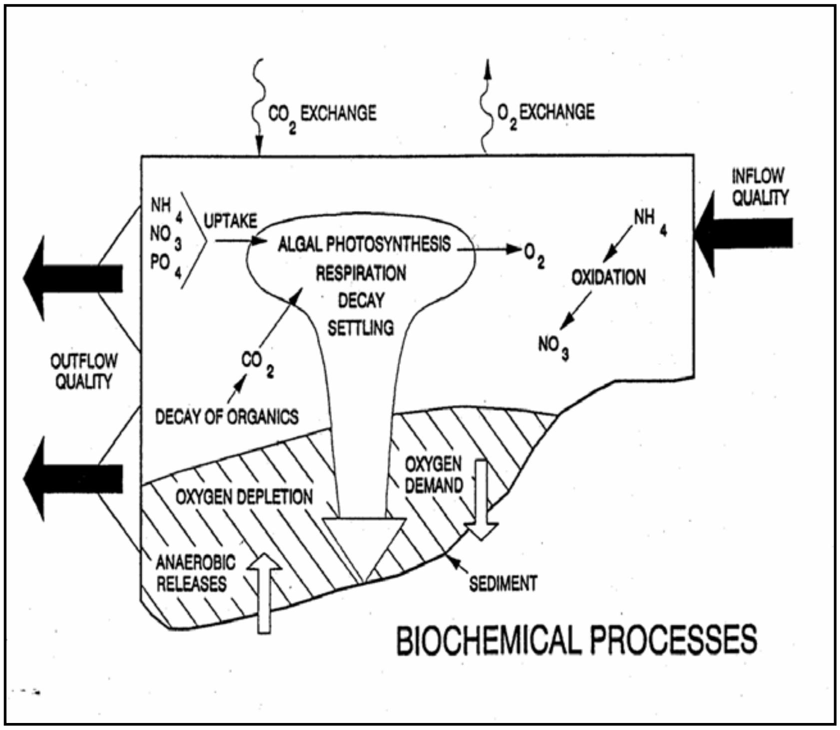

Figure 3.—Major biochemical processes modeled in reservoirs (Bender et al, 1990)

Simulation Model Data Requirements

Numeric computer models created to simulate dynamic riverine characteristics require an extensive array of equations, coefficients, and measured data that are used to express specific hydraulic transport, heat transfer, and biochemical transformation properties of the river reaches. Complete sets of meteorological, water quality, and hydrologic data at the appropriate daily or hourly time intervals are required for all low flow or high flow conditions used for initial model calibration. In addition, accurate measurements of physical dimensions, hydraulic structure (weir) configuration, and operations data are required to represent controlling conditions for the reach-specific model. Original design drawings, as-built design drawings, and Project Data (Bureau of Reclamation, 1981 and 2002 http://www.usbr.gov/dataweb/) specifications should be verified and used with caution.

Data compilation and analysis are critical factors in model development. Complete data sets are required to develop a riverine model, and complete reference data sets for selected flow conditions (ramping, floods, and low flow drought conditions) are necessary to calibrate the base model against known conditions. The model water mass balance and computation time step are essential to model performance. For example, “less than hourly input” data sets are required for the entire week to capture diurnal effects, hourly changes in meteorology, or peaking-power fluctuations. Daily output data may be more useful for internal boundary condition (weir) inputs, multi-month simulations, or other instances where hourly-output fluctuations may not be needed.

Model results can often be improved with accurate channel geometry, planned model construct based on specific questions to be answered, and a computational node-reach configuration designed to capture hydrodynamic, thermal, and water quality constituent gradients. Typically at each pool, three or four cross sections with below-water-line information are adequate for tailwater modeling. Shorter and more longitudinal segments are used at bridges, steep areas, and other places where rapidly changing channel geometry occurs. Some models allow interpolation between measured cross sections. Geometry developed by cross-sectional channel surveys on hydraulic controls, which capture the vertical and horizontal hydraulics controls, are recommended over cross-sectional channel surveys that randomly are taken without intent to develop a horizontal cross section. Random survey points may cause significant post-processing and subjective assumptions during processing of survey data for model geometry development. Less than hourly timestep data are typically required for intermittent peaking-power or other intermittent pumping operations affecting inflows or outflows to the tailwater. Inflows, outflows, inflow temperatures, outflow temperatures, meteorology, and stage gage information are required to capture hourly water mass balance and diurnal thermal information for model hydrodynamic and temperature calibration.

River Model Physical Configuration and Computational Grid

Accounting for hydraulics, such as vertical and horizontal hydraulic controls, during model construct and water mass balance computations is critical in developing fully functional, accurate simulation capabilities. Major factors include accurate stage gages and inflow information as well as inflow and outflow data sets for all major tributaries and discharges.

Riverine tailwater models are often used in conjunction with an upstream reservoir model. Entire systems may link several reservoir models with tailwater models in between. The output from one model serves as the input to another.

Representative Flow Conditions and Data

Selecting low flow periods to calibrate dry, ramping, flood, or spike flow conditions is a key factor in developing a riverine model. Selected months are usually during the warmest time of the year. Months in which mean streamflows are nearest to the 7Q10 (the lowest 7-day average flow that occurs once every 10 years) for a year with the annual mean minimum streamflow conditions are desired. However, in many cases, years with the most complete data sets are chosen.

New, continuously recording thermistors and meteorological stations with modern instruments installed in the near vicinity produce more accurate less-than-hourly inflow water temperature and meteorological data for use in riverine modeling. Wind effects and cloud cover affecting solar radiation are a concern for using meteorological data available from meteorological stations not located near the study site. Horizontal cloud cover reported near airports as miles of pilot sight distance are not useful for estimating cloud cover. Shortwave solar radiation and other parameters taken at agricultural meteorological stations are usually one of the more common data sources for riverine modeling. However, meteorological stations that are installed near the river specifically for modeling purposes tend to produce better results.

Model Calibration and Testing

Riverine models are first calibrated to hydraulics by wave travel time and water travel time. Wave travel time, which is approximated by wave celerity, is much quicker than water travel time of a water particle approximated by a Lagragian particle tracking scheme. Wave travel time is determined from continuous stage elevation at a downstream stage gage by calibrating to a wave (pulsed increase in flow) going by. Water travel time is typically calibrated by using a modeled Lagragian particle tracker built into the code and comparing to dye travel time studies. Alternatively, float travel time of rafting company data and so forth can be used. Dumping a bag of labeled oranges while kicking or tossing stranded oranges out of eddies from a canoe or kayak floating downstream with the wave of oranges can be used to approximate travel times. Such rough float time data typically lies somewhere between actual wave and water travel times.

Riverine models are basically approximations of backwater caused by channel roughness and are calibrated by altering the friction coefficients or model geometry. For high flow conditions, friction is important. For low flow conditions, water travels around boulders and over vertical hydraulic controls, therefore accurate bottom channel geometry becomes much more important at low flow. Many riverine models can adjust the friction coefficient as a function of flow and depth to improve overall calibration.

Temperature calibration involves matching the magnitude and timing of peaks and drops in water temperature at several sites along the river. If water is traveling too fast, channel friction (Manning’s n) can be increased. However, model coefficients related to heating the streambed and bed heat transfer to the water column can also be adjusted. On shallow rivers, bed heat transfer is a significant variable that is overlooked in some models. Fortunately, RQUAL has bed heat transfer incorporated and tested. Often, complete meteorological data and tributary temperature data improve the temperature calibration. Local inflow temperature from shallow groundwater inflow may be fairly constant and may need to be measured or estimated and adjusted during temperature calibration.

RQUAL model DO calibration involves coefficients related to submerged macrophyte respiration, algal photosynthesis, stream aeration equation type, and sediment oxygen demand (SOD). Typically respiration and night processes are calibrated first. Daily photosynthesis and day time processes are calibrated next. Finally, a blend of the day and night processes are calibrated. Calibration of individual processes is typically accomplished by turning off rates to isolate and concentrate on a specific process. For example, night respiration can be investigated by turning off photosynthesis and other processes during that portion of the calibration.

After calibration, an initial series of tests are conducted on the calibrated model to examine the effective range of model application. Boundary condition scenarios and sensitivity tests are performed to define model limitations and examine simulation responses to major forcing functions. Sensitivity evaluations assess the effectiveness of potential aspects of water quality management options. The main goal of sensitivity analysis is to identify major factors affecting flow and water quality and to formulate specific scenarios or alternatives for more detailed study.

Calibration to historical data collected under a range of dry to wet hydrologic conditions is required for simulation of future alternatives. Without model calibration to the range of conditions expected, future modeled scenarios that change inflow or outflow operations outside the calibration range should not be trusted. If inadequate boundary conditions exist, sensitivity testing should be conducted to determine the magnitude of uncertainties due to incomplete data sets. The key to defensible modeling results is reduction of uncertainty and errors in addition to calibration to observed conditions. There can be errors in data design, collection, processing, analysis, and archival. Additional errors occur in model code, model construct formulation, model computations, and interpretation of results. Reducing errors due to inadequate geometry and input data are critical to model accuracy. However, this may require several years of data collection to capture a range of conditions and to minimize errors. Monitoring data are often not adequate for model calibration. A model is only as good as the data that goes into it. All models are incomplete. However, with adequate data and an experienced modeling team, most modeling attempts are extremely useful and predictive.

Other Model Data Collection Considerations

Model development should also consider methods to expand capabilities as necessary to integrate other water quality parameters or to simplify analysis. For example, bioenergetics modeling studies are tied directly to river temperature and productivity, so detailed riverine models may be used or may not be necessary to evaluate alternatives. However, internal process modeling may be useful to evaluate transport and temperature effects on riverine fisheries. In addition, since alternatives to manage riverine fisheries could also influence other processes, the ability to combine temperature, habitat, and fishery bioenergetics modeling simulations in one modeling system may have advantages. These factors can affect the model development approach considerably.

The latest version of the RMS offers advantages in terms of the available simulation capabilities, continued development and support of new subroutines, and output processing features that can be used to assist in interpretation of results. Results for this type of model construct could be useful to investigate riverine characteristics of lotic environments and to evaluate different structural or operational alternatives for water quality management or assimilative capacity. These capabilities could also be used to provide more detailed testing of coordinated data collection and management in a basin by several agencies.

Successful modeling projects require extensive planning; model selection, data collection, sample processing, archival, analysis, presentation of results, and interpretation that support the data quality objectives (DQOs) and QA plan are required.

QA integrates DQOs, Standardized Operating Procedures (SOPs), and approved methodologies (protocols) with a written description of details and delineates responsibilities in a QA Project Plan (QAPP). QA is not QC. QC asks if we are doing things correctly; QA asks if we are doing the correct things. One of the first steps in a DQO planning process is development of the SAP. The SAP is the document which specifies tasks and provides technical procedures to be used in collecting samples and performing analysis for environmental measurements so that quality objectives determined in the DQO planning process are met. The following QA/QC references have been adopted by Reclamation field personnel:

> Bureau of Reclamation, revised August 2003. “Quality Assurance Guidelines for Environmental Measurements.” U.S. Department of the Interior. Originally prepared by QA/QC Implementation Work Group, 1994.
>
> Bureau of Reclamation, September 2003. “Technical Guidelines for Water Quality Investigations. U.S. Department of the Interior.

River Cross Section and Topographic Data

Riverine topography in the form of cross-sectional channel geometry is used to develop the computational model grid. The physical geometry controls the hydraulic properties represented, which influence many associated riverine water quality processes. Cross-sectional channel geometric data are used in 1D models to develop a riffle pool longitudinal representation of the river for numeric computations.

Several methods are used for collecting cross-sectional channel geometry. Historically, survey crews were trained to shoot straight cross sections across the channel perpendicular to flow direction at vertical and horizontal controls at the head of a pool, at the bottom of the pool, on the pool control, and downstream of a pool as x and y data with the cross section location referenced by river mile from the mouth or some known marker. Unfortunately, modern surveys provide x,y,z data without being tied to river miles. The scatter with modern surveys results in large amounts of time spent on post processing the survey data into cross sections from points randomly scattered around the area of the cross section. This introduces error. River reaches may need to be developed based on a longitudinal profile of the thalweg of the riverbed. It may be necessary to re-slice the longitudinal segments, depending on potential problems with the geometry that may cause stability problems or to interpolate between cross sections. Geometry that accurately captures water travel time in major pools is likely the single most important component of riverine modeling. Many errors and inadequate water quality calibrations can often be traced back to poor geometry development techniques.

Alternative Riverine Topographic Data Sources

Cursory assessments with limited funding may use available cross-sectional channel geometry and other rough topographic data sources. Existing model geometry, cross-sectional channel geometry tied to a vertical datum, area-capacity of pools, and other auxiliary data may be helpful in developing geometry. However, the resulting coarse geometry should only be used for appraisal level studies until accurate riffle-pool geometry can be developed.

Example of data collection for a dam tailwater model

Before a riverine modeling project begins, it would be helpful to determine what data are available for the tailwater below the dam. If enough information is available, a preliminary tailwater flow and temperature model could be assembled and used for determining data gaps. A dissolved oxygen calibration is usually about three times more work and should not be attempted before an adequate flow and temperature model is available. Tables 2, 3, and 4 are lists of items that have proven useful in previous studies for temperature model calibration. The information lists include other variables such as dissolved oxygen which may not prove useful in the immediate temperature calibration yet may be needed in years to come to answer other questions related to dissolved oxygen (DO). When looking for data, it is usually best to determine an entire inventory of what is available. A temperature model is also the foundation for a dissolved oxygen model. Dissolved oxygen data is not required to run the temperature model since estimated dissolved oxygen values can be inserted as placeholders and the dissolved oxygen coefficients turned off. However, if the dissolved oxygen data is available or needed at a future date, it is wise to plug it in or collect the necessary data at the same time flow, meteorological, and water temperature data are collected.

To adequately reproduce temperatures, it is critical to determine the volume of water held in the channel by the river at low flows. This requires good cross-sectional channel geometry that adequately represents the riffles and pools and most importantly captures the correct water travel time in each river reach. The best data sets for calibration are those in which a variety and large quantity of data was taken at a known flow condition for several days. Since an unsteady flow model will likely be used, it does not matter if flow values change as long as the times at which the flow values were changed are known.

Any reports with site or vicinity maps or discussion of the area geology, water quality, biology, hydraulics, flow duration (by season or months), dam releases, dam structural characteristics, and upstream water uses are also helpful.

Tables 2, 3, and 4 are "wish" lists of data types for modeling the tailwater, selective withdrawal for input to a tailwater model, and a 1D Reservoir model with completely-mixed vertical layers to determine seasonal temperature inputs to a tailwater model. Table 2 indicates types of data that can be used in calibrating a flow, temperature, and DO tailwater model. Adequate geometry is the most critical element. Table 3 indicates types of data that can be used in calibrating a selective withdrawal model. The selective withdrawal model may be used to determine the dam release temperature which can be an upstream boundary condition for the tailwater temperature model.

Table 4 indicates types of data that can be used in calibrating a one-dimensional (vertically stacked thermal layers) reservoir model such as CE-QUAL-R1 (R1) (USACE, 1982). A one-dimensional reservoir modeling effort may not be necessary if it can be shown that the irrigation or other major reservoir withdrawals upstream of the dam do not affect the reservoir stratification to any great extent. This might be determined by examining reservoir profiles before and after these withdrawals are turned on or off. There are few cases in which CE-QUAL-R1 is used. CE-QUAL-R1 is difficult to use successfully since it is neither well supported nor used anymore. Instead, two-dimensional models are used for reservoir modeling.

For reservoirs longer than about 5 miles, a two-dimensional model with vertical layers and longitudinal segments, such as CEQUAL-W2 (W2) (Cole and Wells 2002 and 2006) or BETTER (Bender, et al., 1990), may be required. Assembling a well developed and supported W2 model is likely less challenging than assembling a less supported model such as CE-QUAL-R1. The pre- and post-processors for W2 and the auxiliary software for W2 simplify assemblage. R1 does not have the same kind of modeling luxuries. Reservoir data collection guidelines (Bureau of Reclamation, 2009) and reservoir model user’s manuals and technical reference guides are available and provide additional information for flow and water quality modeling of impoundments and covers the use of W2.

Table 2. Field data used for hourly flow and temperature tailwater model calibration.

Description of Dam Release and Tailwater Data Types
1) <u>Cross-sectional channel geometry</u> (elevation versus distance perpendicular to stream flow) tied to a known vertical datum and river mile. The distance that each cross section is from the dam (upstream boundary) is required. Cross sections that are not tied to a vertical datum provide an indication of the channel shape and are useful. Cross sections which capture the channel bottom (the part underwater at low flow) are of most use. Cross sections above, at, and below (3 or 4 to a set) each major hydraulic control (which causes formation of a pool) are extremely useful for identifying major volumes (pools) which contain most of the water travel time. The water levels marked on the cross sections at the time of surveying (and the estimated flow) are extremely useful. Flood-plain cross sections are of limited value however may provide information at flood flows (which may be useful in answering questions relating to flooding or bank erosion). Cross sections tied to a known datum are the most important information needed to adequately reproduce flow and temperature patterns. Good model calibration relates directly to adequate geometry. Typically three to five cross sections per mile and a set of three cross sections at each major hydraulic control is adequate to reproduce the geometry of the tailwater. Cross sections in digital (distance from bank versus channel bottom elevation) or graphical form can be used.
2) <u>A channel bottom profile</u> (elevation of channel bottom versus mile) to determine the pool volume and location of hydraulic controls. This thalweg information is extremely valuable and should be found or collected before collecting cross-sectional channel geometry to facilitate locations of riffles and pools. If the bottom of the channel is known, a typical or nearby cross section (general shape) can be raised or lowered to reproduce the volume (pools) in the tailwater. Float studies (canoes or rafts) where depth of pools was recorded by dropping a weight from a labeled rope at a baseflow condition could be useful. Instream flow incremental methodology (IFIM) studies, habitat studies, or biological studies may also have useful geometric information.
3) <u>Low altitude aerial photography</u> (scale 1inch = 400 ft or less) at baseflow or small turbine flow (or some other known flow in the channel) taken before a field survey. The photographs are used to pick out the riffle/pool sequence (hydraulic controls) and determine possible cross section locations for field survey crews. The photographs (especially oblique photographs taken from a helicopter at an angle to the river) give some indication of the volume of water in the pools which is useful for travel time calibration. Photographs also give some indication of the channel friction factors such as fallen trees, weeds, or boulders and the effective barrier height (ratio of tree or canyon wall to distance from stream edge) for determination of shading.
4) <u>Water travel time</u> determination from a tracer. If a known flow pattern and the time that a tracer (Rhodamine WT (red) fluorescent dye, fluorine (yellow) fluorescent dye, spilled contaminant, chlorine, oranges, or low level turbidity current released from the dam) travels a known distance are available, the model water travel time can be calibrated. Water or particle travel time information is extremely useful for riverine model calibration.
5) <u>Wave travel time</u> determination with a downstream stage gage located some distance from the dam. If a known flow pattern and the time that a wave (rise or fall of stage) is known, the model wave travel time (which is usually 2 or 3 times faster than the water travel time) can be calibrated.
6) <u>Hourly releases</u> at the dam or hourly stages in the pool below the dam (upstream boundary condition) and flow or stage at any point downstream from the dam to determine local inflow from tributaries (water gain) or evaporation (water loss), and groundwater recharge (water loss or gain).

Flow or stage at a downstream gage location could be used as a downstream boundary condition. Stage changes, due to tidal fluctuations at a downstream boundary condition, are useful for model calibration of downstream water surface elevation changes and reversals of flow. Watershed drainage areas (for modeled river reaches) along the river are also useful in determining local distributed inflow. A description of the local tributary location (river mile from dam) and the estimated amount of baseflow from each tributary would be helpful. Any rating curves (elevation versus flow) at any of the stage gages would be helpful.

7) Water surface profiles (elevation versus distance from dam) at baseflow, a known flow (turbine, spill, or flood), and the high water marks. Low to medium flow calibration data is typically desired for water quality investigations. However, high water marks during known flood flows are also useful.

8) Temperature measurements. Continuous temperature measurements at known flows or stages are quite useful. Spot temperature measurements at the cool and hot parts of the day or minimum and maximum temperature readings from continuous data can be used to define the daily temperature swings. Main stem and tributary temperatures which define the seasonal temperature patterns are also useful. Continuously recording thermistors left in the river at several locations provide a wealth of inexpensive information and daily minimum and maximum values are often archived.

9) Hourly meteorological data that coincides with the flow information is required for temperature model calibration. Meteorological information should include cloud cover (fraction of sky 0 to 1.0), drybulb (air) temperature (C), dewpoint temperature (C), barometric pressure (mb), wind speed (m/s), and short wave solar radiation (kcal/m2/hr).

10) A description of the channel bottom (gravel, rock, granite, limestone, brown, red, etc.). This information is used to estimate the thermal diffusivity, heat storage capacity, and albedo (reflectivity) of the bed.

11) A description of microclimate conditions such as when the fog cover lifts (6 or 8 am) and how often fog cover is observed (once a month, once a week, etc.). The estimated amount of precipitation by month (for example 30% or 50% in March and April) and average yearly precipitation (for example 8 inches or 12 inches) would be helpful.

12) Critical temperature limits for fish and threatened or endangered species. A listing of the temperature sensitive species (brown trout, rainbow trout, etc.) or the threatened and endangered species (salmon, chubs, suckers, pikeminnow, darters, mollusks, etc.) would be helpful. The estimated instantaneous maximum temperature (for example 24 °C), the 3 to 4 day tolerance maximum temperature (for example 23 °C), and the maximum rate of change (2 °C per hour) for the various temperature sensitive species would be helpful.

13) Fine contour topographic maps (usually 1 or 2 foot contours). This information (also called Kelsh topography) is rare and useful.

14) Release dissolved oxygen (DO) and tailwater DO (at known flows) at locations downstream of the dam. This information would be useful for a DO calibration which is an input for bioenergetics (fish growth) modeling. A low DO slug tracked with particles in the flow (Lagrangian sampling) or a cold water release may also serve as a tracer.

15) Carbonaceous (CBOD) and nitrogenous (NBOD) information (BOD and ammonia) for possible dissolved oxygen (DO) calibration and tracing of releases with low DO. This information

might be used for a DO calibration. DO, CBOD (or ultimate), NBOD, turbidity, and conductivity are commonly collected during water quality surveys in which temperature is recorded.

16) Turbidity, algal biomass, or chlorophyll measurements to estimate light extinction.

17) Flow duration curves or tables which indicate the change in monthly or seasonal flows based on historical data are useful in determining seasonal effects and effects on spawning.

18) A worst case (7Q10, 3Q20, 3Q3 or dry year) flow data set and a hot day meteorological data set for cloudy and sunny cases would also be useful.

19) Dam release temperatures at known flows and a known date. Specific release temperatures taken during a flow, reservoir profile, or tailwater temperature study are useful. Seasonal or monthly release patterns are also useful.

20) An indication of the submerged vegetation or algal growth. This information which is often qualitative gives indication of the channel friction and the photosynthetic/respiration rates.

21) Information on aeration rates which is usually determined during DO studies.

22) ADCP flow measurements at select model node cross sections to estimate seasonal and stream flow rate related reach gains and losses while also checking flow gages and near-by well water table levels.

Table 3. Field data used for selective withdrawal model calibration.

Description of Selective Withdrawal Data Types
1) A cross section of the reservoir just upstream of the dam (forebay cross section). Cross sections from sediment surveys (sediment deposition studies) or the original cross section used to design the dam could be used.
2) Reservoir forebay profiles (constituent versus depth) that are about 200 feet to a quarter mile upstream of the dam. The profile should reflect the depth at the dam while minimizing the near field effect of flow releases (turbine, spill, or river outlet works) on the profile. Temperature, dissolved oxygen, and conductivity profiles all provide information on stratification. Release temperature, dissolved oxygen, and conductivity measurements at known flows that correspond with the reservoir profiles are used to calibrate the selective withdrawal model.
3) Reservoir water surface elevation that corresponds with the profiles.
4) The withdrawal level elevations (lower sill, upper sill, and centerline of the outlets) and a description of the outlet settings (circular pipe, square, gate setting increments, changes to the design drawings, type of modifications possible, etc.)

Table 4. Field data used for a daily one-dimensional (vertically stacked thermal layers) reservoir model calibration.

Description of 1D Reservoir Completely-mixed Layer Model Data Types
1) Cross sections of the reservoir. A cross section at or just upstream of the dam and cross sections throughout the reservoir. Cross sections from sediments surveys (sediment deposition studies) are typically used. The horizontal cross-sectional area, the length, and the reservoir width at the dam for each layer could be model inputs in conjunction with an area-capacity versus elevation curve of the impoundment.
2) Historical daily reservoir inflow and corresponding daily inflow temperature measurements.
3) Daily meteorological data including air (drybulb) temperature, dewpoint temperature (or wetbulb temperature and relative humidity), cloud cover (or shortwave solar radiation), and wind speed.
4) Statistical correlations between daily inflow temperature and air (drybulb) temperature, dewpoint temperature, solar radiation, flow, or other measured parameters. These statistical correlations could be used to estimate inflow temperature based on the day of the year.
5) Daily reservoir releases (cfs). The turbine, spill, sluice, and river outlet works flows should each be separate data variables if possible rather than one combined number.
6) Elevation of reservoir water surface (daily or smaller timestep if possible).
7) Starting and periodic reservoir profiles of temperature, dissolved oxygen, electrical conductivity, or other parameters. Corresponding water surface elevations would also be useful.
8) Daily reservoir withdrawal information or irrigation diversions. These would be simulated as a pump withdrawal or dam outlet.
9) Outlet invert and centerline information such as irrigation withdrawal (diversion canal) bottom elevation and estimated centerline elevation of flow withdrawal.
10) Bottom slope of the reservoir just upstream of the dam (inflow bays).
11) Reservoir channel bottom profile (channel elevation versus mile).
12) Daily number of hours of zero turbine discharge for each month (average).
13) The information for the selective withdrawal model given in Table 3.

Cross-sectional channel geometry survey methods

Accurate river surveys include a below the water surface representation of the river. Flood cross sections that extend into the flood plain are typically not detailed enough for low flow studies. However, most geometric data can be used in the ADYN/RQUAL model by truncating flood plain cross sections at the river bank. For low-flow studies, cross sections should be less than about 12 feet deep to minimize layer thickness and interpolation of data. Too many data points on a cross section increases data input and computation time of the modeling. Less than about 100 x-y data pairs per channel cross section are recommended for modeling.

Cross-sectional channel surveys use two methods. The straight line of sight method is typically used in conjunction with a river mile station survey as discussed in Appendix B. This system takes cross sections perpendicular to the line of flow and tries to represent what a drop of water experiences on its route downstream.

A second more common method of channel survey is a measuring device that uses a global positioning system (GPS). GPS is often used to give an Easting and Northing way-point with a specified accuracy. Unfortunately, often a random non-straight way-point grid of points is typically collected and cross sections computed manually which is time consuming and challenging. Such a computation procedure necessitates mathematically collapsing the various points to a straight line chosen at a later time which introduces error.

Aerial coverages derived from geo-referenced Light Detection and Ranging (LIDAR) data, in conjunction with contours digitized from a topographic map, might also be used to roughly approximate cross sections or extend cross sections into the flood plain if needed.

Digital Mapping Data Format and Processing

All elevations need to be tied to a common vertical datum, which is usually chosen as “project datum” or the commonly used North American Vertical Datum of 1988 (NAVD88) (Ferrari and Collins, 2006). All coordinates are tied to a horizontal projection. Units for vertical and horizontal datums may be different and need to be converted to common units. Care must be used when processing GIS data. Choosing a poor interpolation scheme and processing method can add error to the analysis. Using software designed to develop the geometry for a particular model is recommended and should reduce human error.

The ADYN model uses distance from the cross section edge and channel bottom elevation in conjunction with a river mile distance along the centerline of the modeled reach. For ADYN, river miles can be given either upstream to downstream or downstream to upstream by changing a model flag. However, river miles from an upstream boundary condition such as a dam structure may help to minimize confusion when presenting model results. For example, it is more straight forward to report results at 5 miles downstream of the dam rather than a distance from the mouth of the river.

Model Computational Grid Considerations

How riverine physical geometry is converted into computational segments in the model depends partly on available data, model approach, and professional judgment. The horizontal layout (plan view) should include inflow and outflow points designed to represent the river reaches or connections within subbasins. The model segments might be adjusted to reflect bridges, gages, and control points such as at the heads of islands that braid the river into multiple channels. These decisions in the model setup are subject to modeler judgment, and may include factors such as run time, computational stability, error propagation, and resources required.

As a result, accuracy and resolution of cross-sectional channel geometrical data must be adequate to support desired model construct; however, it does not necessarily dictate the approach taken. The computational grid must consider the other types of model computation and calibration data. In general, higher resolution topography allows greater flexibility in developing the computational representation and, ultimately, can facilitate model application and improve results. However, too many data points per cross section will seriously slow down the model.

There is often a tradeoff between the number of computational elements, the number of data points, and the computation run time and stability of a hydrodynamic model. There also may be certain areas in the river which are problematic in terms of modeling. For example, deep pools may stratify causing warm water to scoot over the top of the bottom cold water portion of the pools thereby negating the completely mixed assumption required for one-dimensional temperature modeling. Such a situation may require modeling more than one reach and additional data at small dams or interim hydraulic structures.

Flows and Water Balance Data

Data representing major water inputs and losses from the system are required for hydrodynamic modeling. This refers mainly to flow and stage data, because precipitation, seepage, and evaporation are included in the local drainage calculation. Adequate flow data are necessary for a range of conditions (e.g., dry, average, and wet) for model testing. In addition, some models such as ADYN/RQUAL calculate error statistics including a final water mass balance.

There are several methods of developing a water mass balance for individual rivers. Typically, known inflow and outflow information, in conjunction with gage water surface elevation, are the basis of a water mass balance. If computed local inflow or flows derived from hydrogeneration data can be obtained from operational models and the analysis of system-wide corrected information, the water mass balance might be fine tuned using a range of hydrologic conditions that vary from week to week. After geometry and modeling construct, an accurate water mass balance is critical for estimating flushing of pools, assimilative capacity, and obtaining accurate water quality calibrations. For developing a water mass balance, there is no substitute for "understanding the accuracy of the data" that goes into the water mass balance and the calibration of outflow temperatures and other water quality parameters. This often requires conversations with field personnel who maintain the gages and collect the data.

Typical mistakes include collecting river temperatures in eddies and other backwater areas not representative of complete mixed conditions. Some configurations require 2-D or 3-D models. Figure 4 (Bender, et al, 2007) depicts the significant temperature differences upstream and downstream of underwater barriers for an assumed quasi-steady state condition modeled with a 3-D Computational Fluid Dynamics model of only the forebay. Such a thermally stratified condition should not be modeled with a 1-D completely mixed riverine model. And sizable weirs located a long distance downstream of a completely mixed dam release may provide challenges for a one-dimensional model which requires breaking the modeling into multiple models with another set of upstream boundary conditions.

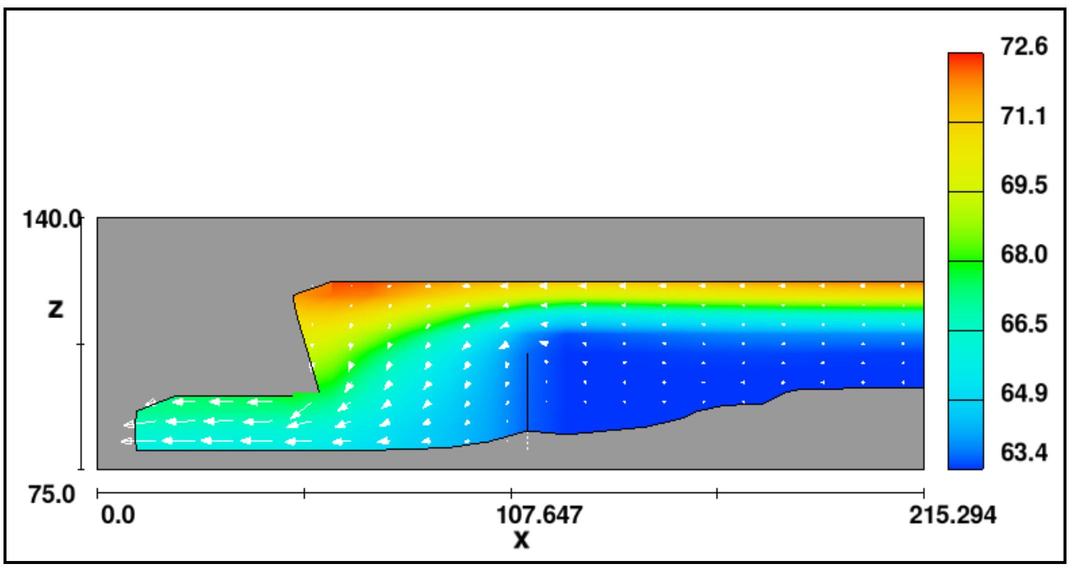

Figure 4.—Modeled temperature contours upstream and downstream of a debris barrier wall in near-field of power plant intakes into a dam (flow direction is right to left). The color contours represent temperature (in degrees Fahrenheit (°F)), x and z distances are in feet, and vectors represent resultant velocities (Bender, et al, 2007).

River Water Mass Balance Data Sources

The methodology for a water mass balance should be tailored to known flow and volume information. Inflow from ungaged tributaries will need to be estimated from nearby streams using watershed drainage area correlations or factored into the combined unknown error and local-drainage inflow component that can be input as distributed local inflow. In some cases, it may be best to apportion some of the error to groundwater outflows or negative distributed local inflow. ADYN/RQUAL calculates a water mass balance over the period of simulation. Water mass balance should be done independently for each period if periods are not consecutive. Other water budget components, including direct precipitation, seepage, evaporation, and other minor runoff components, may need to be estimated or derived for the model.

Flow Monitoring and Data Compilation

Riverine models are ideally calibrated to data sets representing low and high flow conditions to improve the accuracy of simulations made over a wide range of conditions. Historic flow records should be reviewed to find a sufficient set of data for calibration. Probability of flow exceedence of annual water year inflow is useful for identifying 10-percent (wet), 50-percent (median), and 90-percent (dry) probability of flow exceedence, as well as maximum and minimum flow for the period of record. 7Q10, 3Q20, and 3Q3 data is often used for low flow water quality studies in riverine conditions when assimilative capacity is a concern. 7Q10 is the lowest streamflow for seven consecutive days that would be expected to occur once in ten years. The 3Q20 is the lowest stream flow for three consecutive days that would be expected to occur once in twenty years. Calibration conditions for low flow riverine environments may also be selected based on hot or cool average air temperature days, or sunny and cloudy days, depending on the expected application.

Water Budget Data Gaps and Model Considerations

Long-term flow records for mainstem riverine and tributary gauging stations are generally much more complete than corresponding water quality data records. Thorough analysis of available flow records could help define model evaluation scenarios and identify water budget issues that could affect model development. In addition, flow data should be examined with respect to river operating conditions and water surface elevations. Some preliminary steps include the following:

- Review an existing model to assess water mass balance characteristics that may require further model development.

- Conduct preliminary analysis of historic flow records to determine representative dry, average, and wet flow conditions for model calibration and evaluate scenarios or action alternatives.

- Collect flow measurements or compare to already collected measurements such as Acoustic Doppler Current Profiler (ADCP) measurements at key cross section locations to estimate water gains and losses per riverine reach.

- Evaluate system wide operational flow data to determine if changes, such as delayed reservoir filling or modified spill practices in recent years, have also resulted in new trends in riverine water quality conditions, such as delayed reservoir turnover resulting in colder bottom releases later in the year. First flush effects from nonpoint sources after a rainstorm need to be considered also.

Reservoir Operations Data

Operations data are not directly required for a simple river model; however, such data are beneficial when assessing structural or operational alternatives. Operations are inherently incorporated in the water budget because total dam release flows are embedded in historical outflow data used in model setup.

Operations Data Beneficial for Riverine Modeling

Hourly data are essential if there are any peaking power generations, ramping operations or storm loadings, either at inflows or outflows from a riverine reach. Acoustic Doppler Current Profile (ADCP) flow measurements may not match flows derived from a system water mass balance, however ADCP flow measurements are widely accepted for providing additional information. Downstream tidal boundary conditions also present a challenging backwater riverine modeling situation.

Short- and Long-Term Riverine Operational Factors

Both short-term and long-term planning issues could influence the approach taken in defining riverine modeling needs. A model development approach could involve stepwise improvements to the existing model construct or may include assembling a new model with improved cross-sectional channel geometric, meteorological, water quality, and operations data sets.

Often, historical operations data are only available on hard copy and in hand-written form. Manual data entry or scanning makes assembling the data sets time consuming. However, data is valuable to the calibration process and all data should be found and analyzed at the beginning of any modeling project.

Single Water Event Considerations

Model development may involve operational changes that occur within a single watershed event such as a prolonged drought or a flood. For example, operations data for powerhouse, spill conditions, or low flow release operations could be isolated to examine effects on water quality within the releases, in the tailwaters, and in lower riverine reaches. This analysis could be applied initially to a wide range of conditions as an overall feasibility test, or it could be oriented towards conditions representing specific flow conditions.

Specific model evaluation scenarios could be defined to guide operations data analysis and pre-processing. For example, operations data could be examined for adequate data and then compared to model analysis from previous studies.

Longer-Term System Operations

Assembling an extensive set of historical hourly operations data of more than one year may be necessary in evaluating long-term seasonal patterns in multi-year release conditions at a single tailwater downstream of a reservoir. Extensive data requirements might also be necessary in addressing questions concerning relationships between multiple-basin water system components or coordinated operating alternative plans. However, riverine models may run into data input restrictions requiring breaking the long term input data set into multiple modeling scenarios. Reservoir operations modeling over 30 or more years may provide a reference for examining certain system-wide conditions or alternatives. One specific year and months within that specific year might then be selected for simulation based on statistical summaries. Initial model development and planning should consider what types of long-term operational scenarios may be of interest.

Data Gaps and Model Considerations

Converting data into electronic model input files is the first step in developing a model. Raw data will have many data gaps, double data points, or incorrect data. A protocol for filling in data gaps and correcting data should be developed and documented for future data set development. Raw data has to be converted and grouped into an appropriate format for model input.

Water Quality Input Data

Riverine water quality modeling requires combined release (total upstream inflow to channel) data in the tailwater, measured boundary input data, and calibration data within the river reaches. Water quality data include physical (e.g., temperature, conductivity, and pH) and biochemical (e.g., CBOD, NBOD, and nutrients) parameters for a dissolved oxygen calibration.

Water quality information can be obtained from data collection and historical information. However, in most cases, there are considerable data gaps requiring a monitoring plan to support the model used. One of the difficulties is estimating carbonaceous and nitrogenous BOD for estimating decay of organic matter. CBOD is ultimate carbonaceous BOD, not BOD5. Ultimate BOD (BODu) is roughly twice the five day BOD (BOD5).

RQUAL has a simple DO formulation which is highly dependent on aeration equation type. At a minimum, the following water quality data are needed for an RQUAL model DO calibration:

- Inflow waters data (at mouth of major inflows, pipes, and local inflow) including: flow, temperature or heat load, DO, and an estimate of CBOD such as BOD5 (5 day for estimating dissolved organics and detritus or dissolved and particulate organic carbon). Hourly, daily minimum and maximum, or at least daily, average inflow temperatures on major branch and tributary inflows are important in determining mixing in riverine reaches. Inflows with flow gages should also have continuous temperature gages or thermistors.

- Riverine calibration data at key locations including: temperature, DO, pH, and BOD5 (estimated 5 day or estimated dissolved and particulate organic carbon). Field data will be plotted in the same format as model results to facilitate model calibration. Therefore modeled and field data should have the same time stamp and the same location along the river.

- Dam release or tailwater data including: flow from each outlet, temperature, DO, CBOD, and NBOD. Output from one calibrated riverine model may be used as input into another model; therefore, inputs to another model should be output from the model being calibrated.

- Tidal stage data for a model set up with a downstream boundary condition.

Temperature and Water Quality Data Used in Riverine Modeling

Many models are initially constructed to examine diel (day and night) water temperatures. If there are no peaking-power facilities, daily flow and temperature data might be used for sensitivity analysis. As hourly data become available, calibration could focus on those areas of interest identified during sensitivity analysis.

A series of at least hourly data should be collected at all riverine gages for calibration purposes. Minimum and maximum temperature gage information is also valuable. Well-mixed tailwater temperatures at or just below the dam are some of the most useful model input data. Installing a thermistor in a well-mixed stream location to continuously collect information at a downstream target location is useful for model calibration. Figure 5 shows diurnal hourly temperature data about 13 miles downstream of Nimbus Dam. Figure 6 shows hourly modeled (line) versus observed field (circles) water temperature for the Nimbus Dam tailwater during late-summer warm weather just below Nimbus Dam. The data in figure 6 has less fluctuation than the data in figure 5. To calibrate downstream river temperatures accurately, dam release temperatures must first be correct as shown in figure 6 which is about 13 miles upstream of the site shown in figure 5. River night temperatures tend to track better than daytime high temperatures in figure 5. Modeled afternoon temperatures lag afternoon

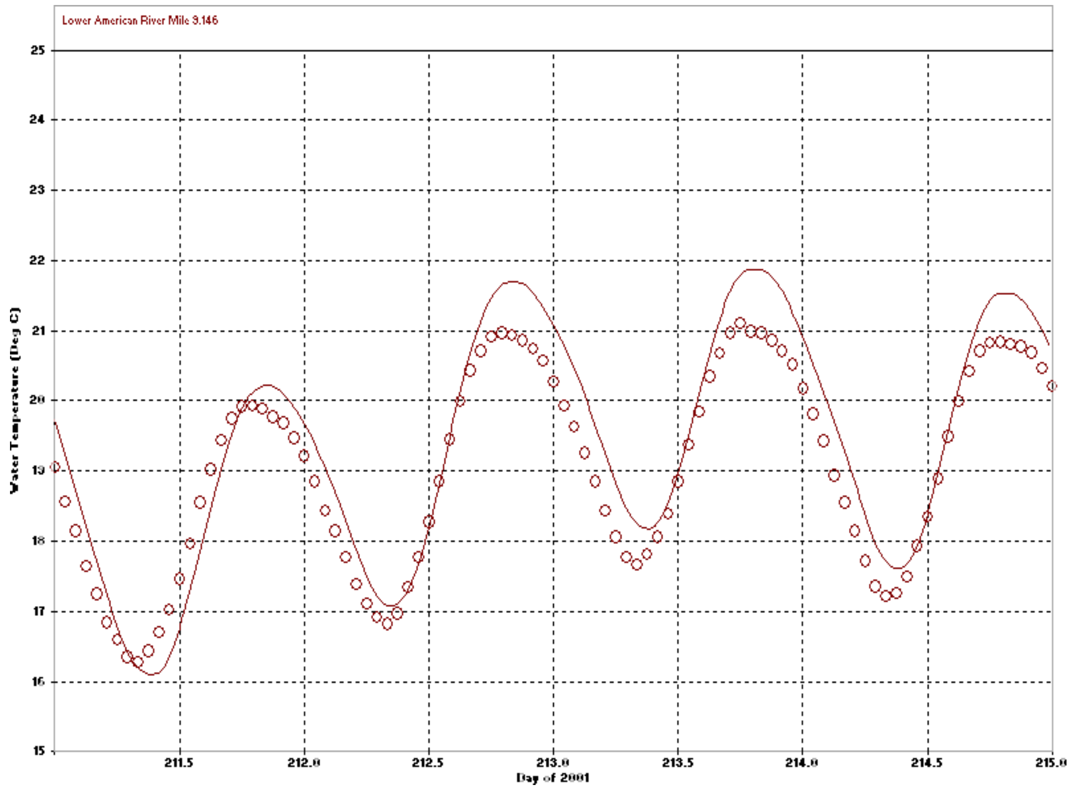

Figure 5.—Modeled (line) and instantaneous observed (circles) temperatures versus time at Watt Avenue Bridge (9.146 miles from mouth) during July 30, 2001, through August 3, 2001 (temperature in °C versus day of year), Bender et al, 2007.

cooling seen in the field. Morning temperatures track accurately in figure 5. Comparing the two figures indicates maximum daily water temperatures heat up about 3 °C (observed) and 4 °C (modeled). The temperature calibration shown is typically accurate enough for answering most temperature questions in a riverine environmental setting.

Salinity data (estimated from electrical conductivity (in µmhos per centimeter) or TDS (in milligrams per liter)) are used in riverine models to indicate general water quality. Salinity and other water quality data is typically not required in most tailwater studies. However, in some cases, it is desirable to use a second water quality parameter in confirming water mass balance and calibration. For example, DO data can be used in confirming the temperature calibration. Salinity gradients can be useful for showing effects of tributary inflow patterns along the riverine reaches.

Water quality parameters might include the interrelated DO, nutrient loading, and eutrophication processes, although obtaining sufficient data for this more involved application is more work and depends on the situation. Higher riverine flow conditions are typically easier to calibrate since errors in input data are quickly washed out of the modeled system. A DO calibration is two or three times more effort than a water temperature calibration. Consequently, expanding the model

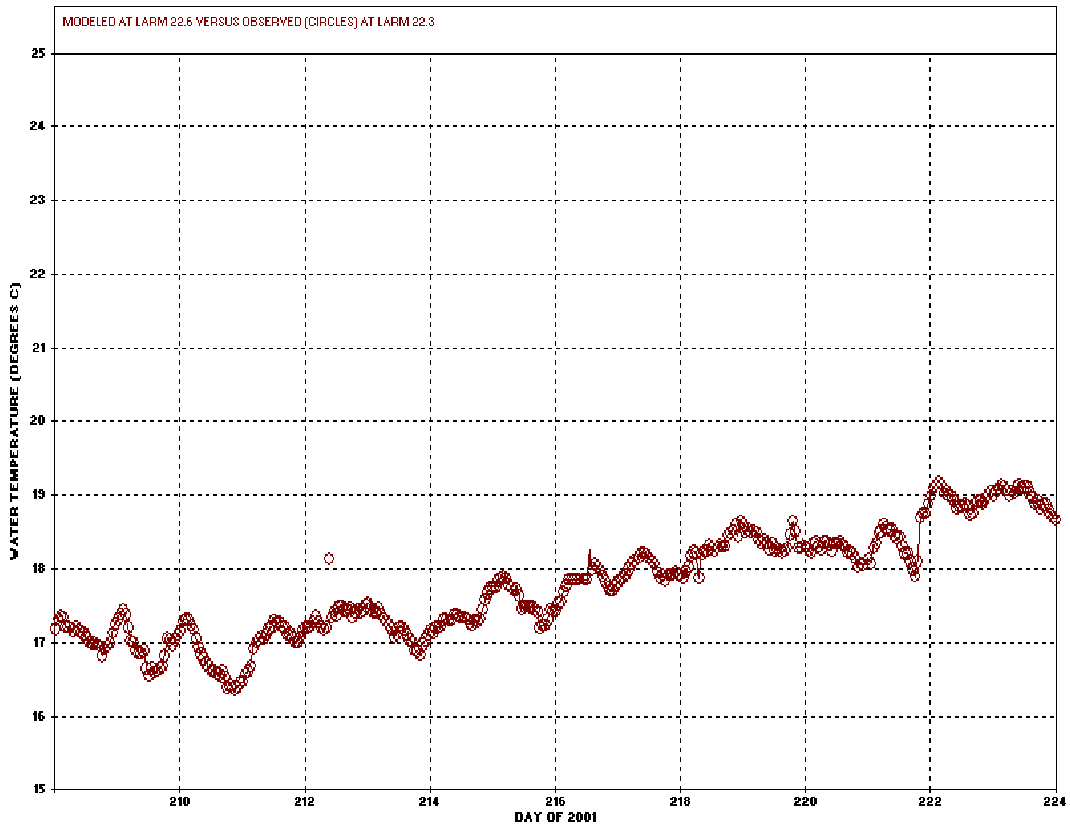

Figure 6.—Modeled (line) and instantaneous observed (circles) release temperature versus time near Nimbus Dam at Hazel Avenue Bridge (CDEC sample site AHZ-LARM 22.3 miles from mouth) from July 27, 2001 to August 12, 2001, Bender et al, 2007.

to support organic decay and prediction of DO concentrations should be carefully planned according to each specific situation. Many temperature models do not include DO and still provide much water quality management information. Spending months collecting data for a DO model may not be recommended if existing historical flow and temperature data are available to calibrate a temperature model and complete the study in a timely manner.

Existing Water Quality Data Sources and Monitoring

Although most temperature studies focus on temperature data, other types of water quality data may be useful for various models in the system. Existing data, system-wide studies, long-term monitoring for analysis of trends, and multi-river-reach model development should be considered when collecting data.

Temperature Data Collection and Processing

Mainstem river temperature data are typically more extensive than data records from tributaries. Some tributary water quality data are often necessary for modeling. Additional data may need to be collected or estimated from a nearby tributary and compared with data from other sources. Often, useful historical data exist and are not discovered until late into the project. Water quality data sources should be searched for and reviewed in detail as part of preparation work for model application. This often requires visiting field offices and talking with those familiar with the watershed and previous studies.

Water Quality Data Collection and Processing

Data must be processed and archived in an electronic format that is readily available for future modeling. Meta data and other field notes should be summarized in a field data report, and raw original data should be stored for future processing. Data collected today may be used many years from now for trend analysis, climate change, or other studies. Data are manipulated by modelers, and multiple versions of the data are circulated. Therefore, observed field data should be preserved and carried forward periodically using different and multiple modern electronic formats.

River and local tributary water quality data, including that for sediment oxygen demand and benthic algae/macrophyte photosynthesis and respiration processes, as well as riparian shading attributes are inputs for some temperature and dissolved oxygen models. Some information for models is estimated rather than measured.

Water Quality Data Gaps and Model Development Considerations

Existing temperature data may be adequate for initial testing purposes. Preliminary model testing may help in evaluating the potential to expand the model for year-round simulation. Analysis of other data sources, including new continuous thermistor data, could help in confirming model data sets and in providing a reference in applying data sets to previous years.

A hierarchical, stepwise approach may be advantageous in refining water quality data only in response to specific model application needs. Temperature is the highest priority for most river models; expansion to include other parameters, such as DO, would likely require additional review and discussion. The following actions include a staged approach for refining water quality data for riverine modeling purposes.

- Conduct a preliminary analysis of available water quality data. Detailed analysis, including statistical analysis and plotting of data, can help to identify trends in the data which are useful in developing an accurate model data set. This analysis is typically done as a preparation step for riverine modeling and is advantageous to help define the appropriate model approach and resources needed for model development.

- Collect physical parameters at selected sites in the riverine reaches that correlate with the inflow-outflow data and would supplement existing historical data. Data at downstream temperature target or water quality compliance sites are important. Several commercially available multi-parameter probes or similar water quality devices can measure temperature, pH, conductivity, and DO. Optional parameters might include nitrates and oxidation-reduction potential (ORP). A week of data collection at three to four stations, including downstream of major inflow tributaries for each major tributary, are suggested for the initial series. Additional sampling sites could be added at a future date, depending on the initial series and analysis of other data sources.

- Conduct initial limited testing of the existing riverine model for evaluating the ability to expand temperature modeling for seasonal simulation and for assessing the need to update the model to a newer research version of the model or the need to add other parameters without coding adjustments. Debugging a new model takes too much time; therefore, using an off-the-shelf version that will answer most of the questions and creatively setting up the model to accommodate special hydraulic situations may be more efficient.

- Evaluate potential action alternatives associated with ongoing basin water use planning and evaluate riverine modeling priorities, water quality parameters, and model support requirements. Cooperation is required between participants who have technical expertise in water quality modeling, river ecology, fisheries, and project operations.

Meteorological Data

Meteorological data are an essential part of riverine temperature models. These data provide the basis for coefficients applied in model equations affecting water quality. As a result, many technical factors are associated with the required meteorological data for those equations.

Hourly meteorological data are typically required for modeling rivers due to large fluctuations in air temperature and solar radiation. There are often numerous National Weather Service (NWS), agricultural, and other nearby meteorological stations. Nearby stations can often be used to provide average hourly meteorological data and to fill in data gaps. However, a meteorological probe extended over the river above the water’s surface is an accepted methodology for river studies.

Meteorological Data for Riverine Modeling

As a minimum, the following information is needed:

Meteorological data including: hourly drybulb (air) temperature (°C), dewpoint temperature (°C), windspeed (meters per second), solar radiation (kcal/m^2/hr), barometric pressure (mb), and cloud cover (fraction of sky) in tenths (0.0 to 1.0). Meteorological data should be determined from the nearest meteorological station recording at 2 meters above the ground and close to the river water surface elevation. For steep rivers with multiple river model reaches, more than one meteorological station may need to be used. Wind speed collected at a different height can be adjusted manually. Missing drybulb temperatures may be derived from maximum and minimum daily temperatures collected at a nearby AgriMet station. Accumulated precipitation and barometric pressure may also be collected at an AgriMet station.

The preliminary model may use meteorological data from more than one source as a calibration parameter. Basic meteorological data including air temperature, barometric pressure, wind speed, and wind direction should be collected from a meteorological station located near the water surface and upstream of the river temperature target location to mimic heating through the reach. Cloud cover and solar radiation data can often be obtained from meteorological stations located at the airports. However, recent not-so-useful horizontal sight distance (0 to 10 miles by 1-mile increments) should not be confused with vertical cloud cover measurements (0 to 10 or tenths of cloud cover) at specified elevations.

Meteorological data influence water quality processes and should reflect actual conditions near the river's water surface. Meteorological data collected miles from the river or at a different elevation may not reflect water surface conditions. Airport stations tend to be far removed from reservoirs and could result in significant differences in wind, cloud cover, or solar radiation measurements from those at the study site.

Meteorological Station Installation

To help resolve meteorological issues, new meteorological stations may need to be installed and maintained to provide a good reference for conditions for the river reach being modeled. The stations might be installed through a cooperative effort and linked into a remote AgriMet monitoring network.

For long rivers or multiple river reaches, more than one meteorological station might need to be installed. Topographic and riparian shading affect riverine modeled water temperature and photosynthesis and may be important to water quality model calibration. Wind speed reduced to near zero by riparian vegetation may increase water temperature. Riparian shading may decrease water temperature. Model calibration requires adequately representing the local conditions which are near the river valley floor. Hill top meteorological stations are often not representative of conditions on the river valley floor.

Deploying Remote Stations and Collecting Field Data

New meteorological data should be reviewed as soon as it comes in. Meteorological station monitoring parameters should be defined to ensure that the data collected would meet the critical meteorological data needs for riverine modeling.

Parameters collected at new meteorological stations may include:

- hourly air temperature—averaged from 15 minute data or determined from mean, minimum, and maximum records

- 24 hourly precipitation—may need corrections if sprinklers are nearby
- Hourly wind speed and wind direction—average conditions for hour
- Hourly solar radiation—global (direct) solar radiation
- Cloud cover as a fraction of sky cover (tenths with 0 as no cloud cover and 1.0 as complete cloud cover)
- Mean hourly dew point temperatures
- Relative humidity—mean daily relative humidity can be converted to daily dewpoint temperature and input required by many models
- Barometric pressure—hourly averages or determined from mean, minimum, and maximum records

Secondary priority parameters, such as pan evaporation, evapotranspiration, and wind run, can be estimated from data collected nearby. If nearby solar radiation was not collected for a historical calibration year, nearby cloud cover data may need to be used during model calibration.

In general, new meteorological station data should provide a good reference for evaluating any spatial effects throughout the river reaches of the watershed and determining appropriate coefficients to include in the riverine model. New data will also provide an important reference for analyzing and adjusting historical meteorological data.

Meteorological Data Gaps and Model Considerations

The following are recommendations for improved data sets for modeling rivers.

- Examine data produced by new meteorological stations often to ensure proper function of equipment and proper QA/QC.
- At the end of warm seasons, review meteorological data, begin setting up methods for data analysis, and begin conversion of new and historic data sets for use in the riverine water quality model.
- Compare newly collected data to nearby meteorological stations at similar elevation. Determine and document differences due to lake effects, major elevation changes, valley alignment, vegetative cover, and topography.
- Delete or note incorrect, negative, or unusually high or low outliers, depending on seasonal conditions.
- Select similar meteorological stations and fill in data gaps in input data sets.

- During development of model input data sets, fill in missing days with hourly data using a previous or following day's pattern. This would depend on nearby meteorological trends at other stations.

- Conduct a site visit to visually see if sampling and meteorological stations appear to be in representative locations.

Data Collection Priorities and Practical Considerations

Discussions with those who have experience in previous river ecology, monitoring, and modeling studies are helpful in gaining insight into technical issues. Practical experience is important to development of modeling capabilities for a river. As a result, a preliminary assessment is considered a critical step to develop improved methods and modeling capabilities useful to examine temperature and other water quality processes associated with riverine model data collection.

The following recommendations are suggested for data collection and initial model development activities for supporting future river ecology studies and ongoing planning.

Prioritizing Critical and Secondary Data Sets

Existing data sources should be reviewed to determine common collection sites and problems with proposed sites. Critical and secondary data sets can then be prioritized. Review the data as it is being collected for problems and visit the site being modeled. It is often better to review historical data, process that data into input files, and develop a test screening model to see where data gaps exist before scheduling a site visit. Investigating which questions to ask and what types of data to request is recommended before scheduling a site visit. It is recommended that a site visit to the river system be conducted to view and talk with dam operators, riverine fishery managers, and other local personnel familiar with past data collection. Often, locals have some unique information (for example, as-built or change diagrams, rather than common design drawings of dam outlets or weir control structures) that can be photocopied or downloaded from computers near the site. Working one-on-one with water quality and water resources professionals at a local office is recommended after a large group meeting with several agencies.

Funding, remote access, and other criteria factors often dictate the amount of data that can be collected. As a minimum, adequate flow and temperature data must be collected at a number of dam outflow (or at a completely mixed location just downstream of the dam), river locations, and major tributary locations. Hourly meteorology can often be found at a nearby site. Visiting the chosen meteorological site during a site visit often can be revealing. Sites installed at either a sheltered site or an open meadow site may or may not match the riparian river cover conditions being modeled. A calibrated temperature model, in combination with DO and conductivity data, can often answer many water quality related questions or can identify dominant water quality issues. However, if low DO, excessive algal biomass, assimilative capacity, and other more complicated secondary water quality issues must be modeled for predicting future conditions, a significant amount of funding should be made available for data collection and modeling. A DO model calibration may more than double the data requirements and modeling efforts when compared to only a temperature model.

If accurate water mass balances are required to track small changes in volume, accurate geometry, inflow, and outflow measurements are required. Initial funding on model geometry is well spent if detailed analysis is required.

A common sequence for model progression is a test screening model before conducting a site visit, a reconnaissance model for sensitivity analysis to identify major factors, an appraisal-level discovery model to identify viable alternatives for structural or operational management options, and a well-calibrated feasibility model that produces defensible results for recommending a well-defined preferred alternative for seeking congressional or agency funding. Increasing levels of data are usually required during each level of the modeling progression to increase the certainty of model results.

Existing Data Sources and Data Compilation

Initial time spent searching for data and talking to those familiar with historical data collection is time well spent. Most projects have data that go undiscovered. Data collection is expensive in comparison to historical data compilation, which often involves data entry from hard copy.

Data compilation should be done with commonly used computer software. Much of the work in developing a model is the processing of geometry and input data for multiple years. Double data points, out-of-expected-range data, and missing data are problematic for hourly data sets, resulting in a time-consuming exercise. Automating data processing is recommended at the beginning of a project because additional years of data might be added later or reprocessed later with a different method. Correcting or developing individual data points manually without a proper or consistent protocol within spreadsheets should be discouraged due to the inability to rapidly replicate the procedure.

Electronic data should be compiled in a format (simple text file) that can be read in the distant future, or a program should be put in place to convert data into a modern electronic format. Multiple backups on different types of electronic media are recommended for long-term storage and archival.

Monitoring Plans and Cost Factors

Initially, the modeler should assemble the best possible historical data set, run the model in a sensitivity analysis, and then visit the field to survey the site, become familiar with terrain, meet field contacts, and gather information for improvement of the data sets and model. After the modeling project is complete, additional monitoring data may be necessary to validate model results and analyze future trends. Cost of additional data collection and future modeling should be factored into the level of modeling recommended at the start of the project. Accurate model calibration requires an entire set of several types of data. If funding is not available to continue collecting full modeling data sets, a future monitoring approach at specific locations could be proposed for long term trend analysis of parameters being modeled, as well as those not included in the model.

Costs for expensive metals analysis and other water quality parameters not modeled with many riverine models should be minimized; however, monitoring data not used in a chosen model may be used in long-term trend analysis. A broad perspective must be considered when laying out a SAP.

Data Review, Analysis, and Processing Concerns

Data collected on the first field trip should be processed, analyzed, and plotted to spot problems or to ensure a complete modeling data set. Adjustments to the SAP may be necessary. Data should also be analyzed and processed in a format that optimizes future usability. Developing a method to minimize data processing and time spent on data formatting and analysis is helpful.

Ideally, data should be processed immediately after collection. Analysis of data includes tossing out bad data and providing corresponding metadata. Processing of data should be optimized and automated by using common standardized software, statistical techniques, and averaging, rather than meticulous manual input and manipulation.

If data processing can be systematically and electronically automated, it will minimize processing time for future data and result in long-term savings. A common mistake is to manually process data without a properly developed protocol. Not developing a protocol introduces error, often results in more wasted efforts as more similar data become available, and results in inconsistencies which make replication of data analysis difficult if the process needs to be repeated.

Conclusions

A calibrated riverine model can be a useful tool for managing the water quality of a riverine ecosystem and investigating fishery conditions. The resulting modeling capabilities are customized to specific characteristics of the river and reservoir system and predefined simulation objectives. Once the complete model is fully calibrated and the effective range of simulation is defined, the resulting capabilities can provide a long-standing resource for predicting and assessing the implications of different management alternatives on dam releases or downstream waters.

Proper collection of complete modeling data sets is critical to ensure adequate model calibration. Data collection for the chosen model should follow development of a SAP and QAPP. After data are collected and processed into a numerical format, it is essential to honor the data by proper digital storage and indexing, along with metadata to record how data were collected and any concerns with the data points.

Documentation of calibration and project simulation alternatives provides future users with critical insight into model formulation, limitations, and range of use. Using a model outside its intended range can result in misinformation and potentially improper decisions regarding the natural resource and aquatic biota.

Automation of data processing saves time and funding. Assembling multiple data sets or multiple models at once in an assembly line mode saves time and reduces error.

References

Ambrose, R.B. et al. 1988. "WASP4, A Hydrodynamic and Water Quality Model—Model Theory, User's Manual, and Programmer's Guide," U.S. Environmental Protection Agency, Athens, GA, EPA/600/3-87-039.

Ambrose, R.B., T.A. Wool, and J.L. Martin, 1993. "The Water Quality Analysis and Simulation Program, WASP5: Part A, Model Documentation Version 5.1," U.S. Environmental Protection Agency Athens Environmental Research Laboratory, Athens, Georgia.

American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF), 2005. "Standard Methods for the Examination of Water and Wastewater," 21st Centennial Edition, Washington, DC.

Bender, M.D., G.E. Hauser, M.C. Shiao, and W.D. Proctor, 1990. "Better: A Two-Dimensional Reservoir Water Quality Model, Technical Reference Manual and User's Guide," Report No. WR28-2-590-152. Tennessee Valley Authority, Engineering Laboratory, Norris, Tennessee.

Bender, Merlynn D., Joseph P. Kubitschek, and Tracy B. Vermeyen, April 2007. "Temperature Modeling of Folsom Lake, Lake Natoma, and the Lower American River," U.S. Department of Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado, Special Report, Prepared for Sacramento Water Forum and the U.S. Fish and Wildlife Service in cooperation with the Mid-Pacific Regional Office, Sacramento, California.

Brown, C. L, and Barnwell, T.O. Jr., 1987. "The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS documentation and user manual:

Athens, Georgia," U.S. Environmental Protection Agency, Environmental Research Laboratory, EPA/600/3-85-040, 455 p.

Bureau of Reclamation, 1981. "Water and Power Resources Service Project Data," A water resources technical publication by the U.S. Department of Interior, Water and Power Resources Service, Denver Colorado, U.S. Government Printing Office.

Bureau of Reclamation, 2002. "Project Data Web," Public information available from the U.S. Bureau of Reclamation Internet Web site: http://www.usbr.gov/dataweb/

Bureau of Reclamation, revised August, 2003. "Quality Assurance Guidelines for Environmental Measurements," U.S. Department of the Interior, Originally prepared by QA/QC Implementation Work Group, 1994.

Bureau of Reclamation, September 2003. "Technical Guidelines for Water Quality Investigations," U.S. Department of the Interior.

Bureau of Reclamation, May 2009. "Guidelines for Collecting Data to Support Reservoir Water Quality and Hydrodynamic Simulation Models," U.S. Department of the Interior, Bureau of Reclamation Technical Service Center, Denver, CO, http://www.usbr.gov/pmts/eco_research/hydromodels.pdf.

Chapra, Steve C. and Pelletier, G.J., November 25, 2003. "QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality: Documentation and Users Manual," Civil and Environmental Engineering Dept., Tufts University, Medford, MA, Steven.Chapra@tufts.

Cole, T.M., and S.A. Wells, 2002. "CE-QUAL-W2: A Two-Dimensional Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.1, User Manual." Draft Instruction Report EL-02-1, Prepared for the U.S. Army Corp of Engineers, Washington, DC.

Cole, T.M., and S.A. Wells, 2006. "CE-QUAL-W2: A Two-Dimensional Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.5, User Manual," Draft Instruction Report EL-06-1, Prepared for the U.S. Army Corp of Engineers, Washington, DC.

Connolly, J.P. and R. Winfield. " A User's Guide for WASTOX, a Framework for Modeling the Fate of Toxic Chemicals in Aquatic Environments, Part 1: Exposure Concentration," U.S. Environmental Protection Agency, Gulf Breeze, Florida, EPA -6--/3-84-077.

Di Toro, D.M., J.J. Fitzpatrick, and R.V. Thomann, 1981, rev. 1983. "Water Quality Analysis Simulation Program (WASP) and Model Verification

Program (MVP)—Documentation," Hydroscience, Inc., Westwood, NY, for U.S. EPA, Duluth, MN, Contract No. 68-01-3872.

Ferrari, R.L., and K. Collins, 2006. "Reservoir Survey and Data Analysis," Chapter 9, Erosion and Sedimentation Manual, Bureau of Reclamation, Sedimentation and River Hydraulics Group, Denver, Colorado, http://www.usbr.gov/pmts/sediment.

Hamrick, J. M. 1996. "A User's Manual for the Environmental Fluid Dynamics Computer Code (EFDC)," Special Report 331, The College of William and Mary, Virginia Institute of Marine Science, Gloucester Point, VA.

Hauser, G.E. and G. A. Schohl, November 2002. "River Modeling System v4—User Guide and Technical Reference," Report No. WR28-1-590-164, TVA River System Operations and Environment, Norris, Tennessee, (Revised June, 2003 in draft).

Martin, James L. and Tim A. Wool, 2002. "Dynamic one dimensional model of hydrodynamics and water quality EPD-RIV1, " Version 1.0, User's Manual, AScI Cooperation, Athens, Georgia, (http://www.epdsoftware.com/Download/EpdRiv1.pdf) .

Novotny, Vladimir, Ehsan Kianirad, David Dedoya, Indrani Ghosh, and Devin McGarvey, 2006. " Review of Watershed Ecological Models," Technical Report No. 7, Center for Urban Environmental Studies, northeastern University, Boston, Massachusetts (http://www.coe.neu.edu/.../TR-7-Review%20of%20Watershed%20Ecological%20models.pdf).

Park, R. A., and J. S. Clough. 2004. "Aquatox (Release 2): Modeling Environmental Fate and Ecological Effects in Aquatic Ecosystems, Volume 2: Technical Documentation," U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USACE, Environmental Laboratory, 1982. "CE-QUAL-R1: A Numerical One-Dimensional Model of Reservoir Water-Quality; User's Manual," Instruction Report E-82-1 (Revised Edition supersedes IR E-82-1, dated April 1982), U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Wetzel, R.G., 2001. Limnology: Lake and River Ecosystems, 3rd. Edition, Academic Press, New York, NY, ISBN: 0127447601.

Wool, Tim A., Ambrose, Robert B., Martin, James L., Comer, Edward A., "Water Quality Analysis Simulation Program (WASP) Version 6.0 Draft: User's Manual," U.S. Environmental Protection Agency, Athens, GA, http://www.epawasp.com/

Appendix A—Riverine Water Quality Models

RMS (ADYN/ADYNEXT and RQUAL/RQEXT)

The River Modeling System (RMS) contains several model subcomponents which are centered on the flow and hydraulic model called ADYN and its matching water quality model called RQUAL. ADYN and RQUAL are decoupled. ADYN can be run first. And RQUAL can be run separately to allow multiple water quality runs based on a common set of hydraulics from one ADYN simulation.

ADYN: (hydraulic model)

- Riverine hydraulics
- One-dimensional, longitudinal, unsteady flow
- Hydraulics of floods and man-made transients (e.g., hydropower releases)
- Effects of dynamic tributary systems and local inflow sources
- Assessment of wetted areas for environmental flow assessments
- Governing Equation: St. Venant Equations
- Numerical solution: (a) four point implicit finite difference, or (b) McCormack explicit scheme (disabled), (c) Holly-Preissmann characteristic method.

RQUAL (water quality model)

- Water quality fate and transport
- One-dimensional, longitudinal, dynamic representation
- Waste load allocation
- Effects of location, magnitude, and timing of interventions seeking to improve water quality
- Dilution and degradation of wastes
- Effects of thermal loadings and atmospheric heat exchange on stream temperature
- Effects of natural or artificial aeration, diurnal photosynthesis and respiration by benthic algae/macrophytes, waste loads, tributary inflows, and variable flow regimes on the dissolved oxygen regime
- Governing Equation: Mass transport equation (advection-diffusion equation with diffusion neglected)
- Numerical solution: (a) four point implicit finite difference, or (b) McCormack explicit scheme

NUMBER OF MODEL DIMENSIONS: One (laterally and depth averaged)
MODEL LANGUAGE: FORTRAN
MODEL PLATFORM: PC (personal computer)

INTERFACE AND PRE-/POST-PROCESSORS:
The River Management System (RMS) includes an interface to display both ADYN and RQUAL output and statistics using the ADPLT (or ADYNEXT) and RQPLT (or RQEXT) post processor programs.

EXPERIENCE: Used extensively by the Tennessee Valley Authority and occasionally by the Bureau of Reclamation Technical Service Center (TSC)

CURRENT VERSION:
__ ADYN: 4.xx
__ RQUAL: 4.xx

INPUT REQUIREMENTS:
ADYN:
__ River geometry
__ River and local tributary hydrology (water surface elevation and flow rate at boundaries)
RQUAL:
__ River geometry (consistent with ADYN)
__ Meteorological conditions
__ River and local tributary water quality, including sediment oxygen demand and benthic algae/macrophyte photosynthesis and respiration distribution, as well as riparian shading attributes.
__ Processes include:

- Temperature
- Dissolved oxygen
- Nitrogenous biochemical oxygen demand
- Biochemical oxygen demand
- Benthic algae/Macrophyte photosynthesis and respiration
- Sediment oxygen demand
- Reaeration

OUTPUT (available at all nodal locations):
ADYN
__ Discharge and water surface elevation
__ Water velocity
__ Water depth
__ Wetted area
__ Travel times
__ Water volume
__ Froude number
RQUAL
__ Water temperature
__ Dissolved oxygen

Select References for ADYN/RQUAL modeling:

Hauser, Gary E., Hadjerioua B., and Shiao, M.C.: *Model Exploration of Hydrodynamics, Water Quality, and Bioenergetics Fish Growth in Bull Shoals and Norfork Tailwaters*; WR98-1-590-174; Norris Engineering Laboratory; TVA, 1998.

Bender, Merlynn D. and Hauser, Gary E., June 1987. *Temperature Modeling to Investigate the Use of Reservoir Releases to Create Trout Fishery Between Apalachia Dam and Powerhouse*; Norris Engineering Laboratory; Tennessee Valley Authority, Laboratory Report No. WR28-1-15-102, June 1987.

Bender, Merlynn D.: *Temperature Modeling of McKay Dam Tailwater*; Department of Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado, Prepared for the Pacific Northwest Regional Office, Boise, Idaho, September 2001.

Hauser, Gary E., Bender, Merlynn D., McKinnon, Mary K.: *Model Investigation of Douglas Tailwater Improvements*; Tennessee Valley Authority Engineering Laboratory Report No. WR28-1-590-143, November 1989.

Hauser, Gary E.: *Breaching of Low Head Dams for Fish Passage on the James River in Richmond, Virginia*; Tennessee Valley Authority Engineering Laboratory Report No. WR28-1-900-170, July 1986.

Hauser, Gary E. and Bender, Merlynn D.: *Model Investigation of Minimum Flow Request for Industrial Cooling Water on the Upper Holston River*; Tennessee Valley Authority Engineering Laboratory Report No. WR28-2-590-141, May 1988.

AQUATOX

AQUATOX is a simulation model for aquatic systems. AQUATOX predicts the fate of various pollutants, such as nutrients and organic chemicals, and their effects on the ecosystem, including fish, invertebrates, and aquatic plants. AQUATOX is a valuable tool for ecologists, biologists, water quality modelers, and anyone involved in performing ecological risk assessments for aquatic ecosystems. AQUATOX now does a better job of simulating attached algae (periphyton) in streams.

AQUATOX is a PC-based ecosystem model that simulates the transfer of biomass and chemicals from one compartment of the ecosystem to another. It does this by simultaneously computing important chemical and biological processes over time. AQUATOX simulates multiple environmental stressors (including nutrients, organic loadings, toxic chemicals, and temperature) and their effects on the algal, macrophyte, invertebrate, and fish communities. AQUATOX can help identify and understand the cause and effect relationships between chemical water quality, the physical environment, and aquatic life. It can represent a variety of aquatic ecosystems, including vertically stratified lakes, reservoirs, ponds, rivers, and streams.

AQUATOX can be used to address a wide variety of issues requiring a better understanding of the processes relating the chemical and physical environment to the biological community. Possible applications of AQUATOX include:

- Developing numeric nutrient targets based on desired biological endpoints.
- Evaluating which of several stressors is causing observed biological impairment.
- Predicting effects of pesticides and other toxic substances on aquatic life.
- Evaluating potential ecosystem responses to invasive species.
- Determining effects of land use changes on aquatic life by using the linkage with BASINS, a commonly used watershed model.
- Estimating time to recovery of fish or invertebrate communities after reducing pollutant loads.

AQUATOX Reference:

http://www.epa.gov/athens/wwqtsc/html/aquatox.html

Park, R. A., and J. S. Clough. 2004, *Aquatox (Release 2): Modeling Environmental Fate and Ecological Effects in Aquatic Ecosystems, Volume 2: Technical Documentation*, U.S. Environmental Protection Agency, Office of Water, Washington, DC.

EFDC

The Environmental Fluid Dynamics Code (EFDC Hydro) is a state-of-the-art hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions. It has evolved over the past two decades to become a widely used and technically defensible hydrodynamic model. EFDC uses stretched or sigma vertical coordinates and Cartesian or curvilinear, orthogonal horizontal coordinates to represent the physical characteristics of a waterbody. It solves three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable-density fluid. Dynamically-coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. The EFDC model allows for drying and wetting in shallow areas by a mass conservation scheme. The physics of the EFDC model and many aspects of the computational scheme are equivalent to the widely used Blumberg-Mellor model and U.S. Army Corps of Engineers' Chesapeake Bay model. EFDC's role in the Total Maximum Daily Load (TMDL) Toolbox will be to provide necessary hydrodynamic inputs to WASP, the receiving water quality model.

EFDC Preprocessor

In order to facilitate the setup and application of EFDC, a preprocessor is being developed. The preprocessor will be composed of two major components: the Curvilinear Grid Generator and the EFDC Model Interface. Together these components will enable users to generate curvilinear-orthogonal grids, simulate aquatic systems in 1, 2, or 3-dimensions, link 2-D grids to 1-D grids, quickly and easily set and change critical modeling parameters, and make use of watershed loading model results and monitoring data for boundary conditions.

The Curvilinear Grid Generator will enable a user to generate curvilinear-orthogonal grids that are required for the numerical model. It will significantly decrease the repetitive effort typically required through manual grid generation methods. Grid generation will be conducted interactively and intuitively through the interface and associated controls. Key features of the tool will include:

- GIS interface
- Model domain designation through user control point designation
- Automatic insertion of grid boundary points based on control point designation
- Automatic curvilinear-orthogonal grid generation
- Model grid conversion to GIS shape file format
- Cell mapping between EFDC and WASP

Once a grid has been generated, it is necessary to set and calibrate pertinent modeling parameters. The EFDC interface can simplify the setup and application of EFDC through a user-friendly graphical interface and associated windows. It can support input of EFDC model run control and model parameter designation, and it can link directly to boundary condition/source data, e.g. watershed model output and point source contributions. Key features of the tool can include:

-Database-oriented interface
-Visual linkage to the model grid
-Visual linkage to point and nonpoint source inputs
-New model parameter addition and accommodation
-Direct linkage to the Water Resources Database (WRDB) for boundary condition designation/generation

EFDC Reference:

http://www.epa.gov/athens/wwqtsc/html/efdc.html

Hamrick, J.M., 1998. “A theoretical description of the EFDC model’s embedded near field mixing zone sub-model,” Tech. Memo TT-EFDC-98-1, Tetra Tech, Inc., Fairfax, Virginia.

Hamrick, J. M. 1996. *A User’s Manual for the Environmental Fluid Dynamics Computer Code (EFDC)*. Special Report 331, The College of William and Mary, Virginia Institute of Marine Science, Gloucester Point, VA.

Hamrick, J.M. 1992. *A Three-Dimensional Environmental Fluid Dynamics Computer Code: Theoretical and Computational Aspects*. Special Report 317, The College of William and Mary, Virginia Institute of Marine Science, Williamsburg Virginia.

EPD-RIV1

EPD-RIV1 is a system of programs to perform one-dimensional dynamic hydraulic and water quality simulations. The computational model is based upon the CE-QUAL-RIV1 model developed by the U.S. Army Engineers Waterways Experiment Station (WES). This modeling system was developed for the Georgia Environmental Protection Division of the Georgia Department of Natural Resources by Dr. Roy Burke III, Program Manager and the U.S. Environmental Protection Agency, Region IV, Dr. Jim Greenfield.

EPD-RIV1 is a one-dimensional (cross-sectionally averaged) hydrodynamic and water quality model. It consists of two decoupled 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 water quality code when performing water quality simulations.

The water 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 biochemical 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).

EPD-RIV1 is the result of a series of modifications to the original COE Waterways Experimental Station (WES) code to improve its performance and add to its capabilities, particularly for performing wasteload allocations. Considerable effort was directed toward making the model easier to use. Several additional programs were developed to aid the user in the development of input datasets for the EPD-RIV1 models and interpret the results. Pre- and post-processors are integrated with the Water Resources Database (WRDB) that was also developed for Georgia Environmental Protection Division (EPD) and Region IV of the Environmental Protection Agency (EPA). This system provides the user with a unique set of tools to aid in the analysis of environmental data, preparation of 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.

The PreRiv1 preprocessor is organized about the *project* concept, in which all the files associated with a hydrodynamic and water quality simulation are identified and stored. Input data files are saved in the standard model input format, but can be edited with user-friendly forms especially designed for inputting modeling data; on-line help explains the required input and offers suggestions for reasonable values for kinetic parameters.

Time series data can be input manually or imported from WRDB or other data sources by mapping one or more stations to model cross sections. The user can interpolate missing values if appropriate, and apply scale and conversion factors during the "build" operation.

PreRiv1 also acts as the control center for viewing data files, running the hydrodynamic and water quality simulation models, examining modeling results using the postprocessor, and running WRDB. When the simulation models are running, intermediate results are displayed in an "interactor" screen; the user can cancel lengthy computations if it is apparent that computed results are inappropriate.

The postprocessor is capable of graphically displaying large (100s of Mb) modeling output files and comparing simulation results with observed data stored in a variety of data sources (usually WRDB). Several graphic formats are available including: time series; longitudinal, depth, and width profiles; frequency histograms and probability plots, and scatter plots. Statistics can be instantly displayed to help the modeler compare various modeling runs or observed data.

PreRiv1 uses spreadsheet-style input forms especially designed for inputting modeling data; on-line help explains the required input and offers suggestions for reasonable values for kinetic parameters.

EPD-RIV1 References:

http://www.epa.gov/athens/wwqtsc/html/epd-riv1.html

Martin, James L. and Tim A. Wool, 2002 “Dynamic one dimensional model of hydrodynamics and water quality EPD-RIV1,” Version 1.0, User’s Manual, AScI Cooperation, Athens, Georgia. (http://www.epdsoftware.com/Download/EpdRiv1.pdf)

QUAL2K

QUAL2K (or Q2K) is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E (or Q2E) model (Brown and Barnwell 1987, Chapra and Pelletier 2003). Q2K is similar to Q2E in the following respects:

- One dimensional. The channel is well-mixed vertically and laterally.
- Steady state hydraulics. Non-uniform, steady flow is simulated.
- Diurnal heat budget. The heat budget and temperature are simulated as a function of meteorology on a diurnal time scale.
- Diurnal water-quality kinetics. All water quality variables are simulated on a diurnal time scale.
- Heat and mass inputs. Point and non-point loads and abstractions are simulated.

The QUAL2K framework includes the following new elements:

- Software Environment and Interface: Q2K is implemented within the Microsoft Windows environment. It is programmed in the Windows macro language: Visual Basic for Applications (VBA). Excel is used as the graphical user interface.
- Model segmentation: Q2E segments the system into river reaches comprised of equally spaced elements. In contrast, Q2K uses unequally-spaced reaches. In addition, multiple loadings and abstractions can be input to any reach.
- Carbonaceous BOD speciation: Q2K uses two forms of carbonaceous BOD to represent organic carbon. These forms are a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). In addition, non-living particulate organic matter (detritus) is simulated. This detrital material is composed of particulate carbon, nitrogen, and phosphorus in a fixed stoichiometry.
- Anoxia: Q2K accommodates anoxia by reducing oxidation reactions to zero at low oxygen levels. In addition, denitrification is modeled as a first-order reaction that becomes pronounced at low oxygen concentrations.
- Sediment-water interactions: Sediment-water fluxes of dissolved oxygen and nutrients are simulated internally rather than being prescribed. That is, sediment oxygen demand (SOD) and nutrient fluxes are simulated as a function of settling particulate organic matter, reactions within the sediments, and the concentrations of soluble forms in the overlying waters.
- Bottom algae: The model explicitly simulates attached bottom algae.
- Light extinction: Light extinction is calculated as a function of algae, detritus and inorganic solids.

- pH: Both alkalinity and total inorganic carbon are simulated. The river's pH is then simulated based on these two quantities.
- Pathogens: A generic pathogen is simulated. Pathogen removal is determined as a function of temperature, light, and settling.

QUAL2K References:

http://www.epa.gov/Athens/wwqtsc/html/qual2k.html

Brown, C. L, and Barnwell, T.O. Jr., 1987, "The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS documentation and user manual: Athens, Georgia," U.S. Environmental Protection Agency, Environmental Research Laboratory, EPA/600/3-85-040, 455 p.

Chapra, Steve C. and Pelletier, G.J., November 25, 2003. "QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality: Documentation and Users Manual," Civil and Environmental Engineering Dept., Tufts University, Medford, MA, Steven.Chapra@tufts.

WASP7

The Water Quality Analysis Simulation Program version 7 (WASP7), is an enhancement of the original WASP model (Di Toro et al., 1983; Connolly and Winfield, 1984; Ambrose, R.B. et al., 1988, Ambrose, Wool, and Martin, 1993). Version 7.4 is primarily a bug fix version with the draft version 6.0 manual as online documentation. This model helps users interpret and predict water quality responses to natural phenomena and manmade pollution for various pollution management decisions. WASP is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. WASP allows the user to investigate 1, 2, and 3 dimensional systems, and a variety of pollutant types. The state variables for the given modules are given in the table below. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model. WASP also can be linked with hydrodynamic and sediment transport models that can provide flows, depths, velocities, temperature, salinity and sediment fluxes.

Table A-1 State Variables for the WASP model

Eutrophication Module	Organic Chemical Module	Mercury Module
Dissolved Oxygen	Chemical 1	**Elemental Mercury**
CBOD (1)	Chemical 2	**Divalent Mercury**
CBOD (2)	Chemical 3	**Methyl Mercury**
CBOD (3)	Solids 1	**Sands**
Ammonia	Solids 2	**Fines**
Nitrate	Solids 3	
Organic Nitrogen		
Orthophosphate		
Organic Phosphorus		
Algae		
Benthic Algae		
Detritus		
Sediment Diagenesis		
Salinity		

WASP7 References:

http://www.epa.gov/athens/wwqtsc/html/wasp.html

Ambrose, R.B, et al, 1988. "WASP4, A Hydrodynamic and Water Quality Model—Model Theory, User's Manual, and Programmer's Guide," U.S. Environmental Protection Agency, Athens, GA, EPA/600/3-87-039.

Ambrose, R.B., T.A. Wool, and J.L. Martin. 1993. "*The Water Quality Analysis and Simulation Program, WASP5: Part A, Model Documentation Version 5.1,*" U. S. Environmental Protection Agency, Athens Environmental Research Laboratory, Athens, Georgia.

WASP version 7.41 webpage: http://www.epa.gov/athens/wwqtsc/html/wasp.html

Wool, Tim A., Ambrose, Robert B., Martin, James L., Comer, Edward A., "Water Quality Analysis Simulation Program (WASP) Version 6.0 Draft: User's Manual," U.S. Environmental Protection Agency, Athens, GA, http://www.epawasp.com/

Appendix B—Instructions for collecting cross-sectional channel geometry using river mile stations.

The primary purpose of a cross-sectional channel survey is for developing modeling geometry, to identify major hydraulic controls, and to baseline sediment movement or channel changes over time. Survey channel geometry that is tied to a vertical datum should be used in a hydraulic model. If accurate modeled water temperature prediction is required, reproduction of the pool volumes and hydraulic controls (riffle-pool) is necessary. A vertical hydraulic control is a vertical raise in the channel bottom which causes formation of a pool. These are usually seen at the downstream end of the pools at low flow and often have white water just downstream. A typical vertical control that can be spotted on topographic maps is the head of an island that causes bifurcation of the river (flow on both sides of the island). A horizontal hydraulic control is a horizontal constriction in the channel which causes the flow velocity to increase.

Low altitude aerial photography and a longitudinal channel bed profile tied to a vertical datum taken or discovered before collecting cross-sectional channel geometry can be valuable for laying out the survey. Some details of a cross-sectional channel survey are as follows:

1) Low altitude aerial photography (scale 1 inch = 400 ft or less) at baseflow or small turbine flow (or some other known flow in the channel) to allow marking of the cross sections on the photographs for the survey team. Marked photographs are an extremely useful communication tool between modelers and surveyors. The photographs can be used before the channel survey to pick out the riffle/pool sequence (hydraulic controls) and determine possible cross sectional channel locations for field survey crews. The photographs give some indication of the volume of water in the pools which is useful for travel time calibration. Photographs also give some indication of the channel friction factors such as fallen trees, weeds, or boulders and the effective barrier height (ratio of tree or canyon wall to distance from stream edge) for determination of shading. Rough pencil marks of where cross sections are located can be marked on the photographs to guide the survey crew. However, the final location should be chosen in the field by an experienced survey crew member.

2) A channel bottom profile (elevation of channel bottom versus river mile) with the corresponding water surface profile (water surface elevations) to determine the pool volume and location of hydraulic controls is useful for identifying vertical hydraulic controls. This information obtained by a detailed survey taken along the thalweg of the streambed is extremely valuable. If the bottom of the

channel is known, a typical cross section (general shape) can be raised or lowered to reproduce the volume (pools) in the tailwater during model calibration. Measuring depths from a boat can provide some riffle/pool information; however, a channel bottom tied to a known vertical datum is most useful.

3) Cross-sectional channel geometry (elevation versus distance across the stream) tied to a known datum are required. However, the distances that the cross sections are located from the dam release point (upstream boundary) in "RIVER MILES" are also needed. For some models such as ADYN/RQUAL, the end of the conduit through the dam can be taken as river mile 0.0 rather than river miles from the mouth of the creek or river. The distance from the dam to a control weir (or other control structure) is required. Cross sections which capture the channel bottom (the part underwater at low flow) are of most use. Cross sections just above, at, and about one tenth of a mile below (3 or 4 to a set) each major hydraulic control (which causes formation of a pool) are extremely useful. Cross sections taken at existing flow gage and proposed ADCP flow measurement sites are also useful. In most cases, cross sections can be taken more than one tenth of a mile apart and may be taken a half mile apart. The water levels marked on the cross sections at the time of surveying (and the estimated flow) are extremely useful. The flood plain portion of the cross sections are of little value in water quality or low flow studies and only provide information at flood flows (which may be useful in answering questions relating to flooding or bank erosion studies). The flow ranges of interest are typically less than 500 cfs. Surveyors should take a cross section in the pool and record the water surface elevation at an estimated low flow. The water surface elevation will provide an indication of the downstream control below the pool. Both the left water edge and the right water edge should be recorded on the cross section. For low flow modeling with ADYN/RQUAL, cross sections should be taken starting at the top of banks but the cross sections should rarely be more than about 12 foot deep. Only about 15 to 25 points (distance, elevation) are typically necessary and preferred over a great number of points. Many survey points will slow down the model and require excessive manual manipulation to systematically toss out during post processing of survey data. Several points are required at the channel bottom where water travels during very low flows. It is necessary to capture the major changes across the cross section of the channel which can affect flow. Cross sections tied to a known datum are the most important information needed to adequately reproduce flow and temperature patterns. To ease confusion and simplify modeling in a basin, project datum is typically used in most projects or referenced to a commonly used vertical datum in the basin such as Above Mean Sea Level (AMSL) or the North American Vertical Datum of 1988 (NAVD88). Note that the National Geodetic Vertical Datum of 1929 (NGVD29) is not the same as mean sea level (MSL). Good model calibration (including DO calibration) relates directly to good geometry. Typically two or three cross sections per mile and a set of three or four cross sections at each major hydraulic control are adequate to reproduce the geometry of the tailwater. More are required at bridge or road crossings and near hydraulic structures. Cross sections

in digital (distance from bank versus elevation), graphical form, or both can be used. The data must be reduced and both the reduced data and photocopies of the field notes should be provided to the modeler. Date and time of each surveyed cross section should be recorded. See the following example of a reduced cross section.

Sample of cross section with numbers and notes after reducing the field notes

4.950 river miles below the dam
location description: in pool before hydraulic control taken at
about an 85 degree angle to the flow, (Jan. 13, 1994, 4:30 to 5:00 pm),
estimated flow about 20 cfs, rock and cobble bottom, no weeds,
some ice on downstream hydraulic control

distance from left bank looking downstream in feet	elevation above mean sea level in feet	notes
21	6588.01	left top of bank
30	6585.24	
38	6583.88	
45	6581.64	
56	6580.23	left edge of water
59	6578.11	
65	6577.92	
81	6577.82	
84	6576.49	
85	6576.25	
87	6576.20	bottom of channel
90	6576.59	
93	6576.78	
109	6577.82	
115	6578.34	
125	6580.30	right edge of water
135	6582.44	
140	6585.98	
153	6587.80	right top of bank

Special notes:

It is important to try and capture both the pool volumes and the hydraulics (what the flow sees as it travels downstream) for the hydraulic model. This may require taking the cross section at an angle rather than perpendicular to the river if the vertical hydraulic control is at an angle to the river. The angle should be approximated and recorded. Draw pictures to communicate if necessary.

The water surface elevation, the type of river bottom (sand, cobbles, rock, etc.), the approximate flow, logs restricting flow, beaver dams, and other notes should be recorded. For instance, a lot of weeds and small boulders will increase the channel friction which is an input to the model. The river's water surface profile is important information since it indicates the location of hydraulic controls.

The river may have cut a new channel in several places, and the old topographic maps likely do not show this. Therefore "river miles" are measured in the field along the approximate center of the current river channel and "not" from topographic maps which may correspond to a historical river channel that has moved laterally over many years.

Summary for surveying cross sections:

1) Need cross-sectional channel geometry with
   a) distance versus elevation tied to a known vertical datum
   b) distance of cross section from dam in river miles
   c) water surface elevation at the cross section at time of survey
   d) description of river channel bottom (cobbles, weeds, rock etc.)

2) Need the channel bottom (thalweg or deepest part) and water surface profiles (at a known flow) to define riffle/pool

3) Need cross sectional channel geometry which define hydraulic controls

4) Need an estimate of the pool volume between the dam and the control structure just below the dam (may require a raft or canoe). Topography between the dam and a control weir (or other structure) may already be available.

5) Need to know the width of any control structure (weir) portion that water flows over.

6) Read and record stage gage heights and corresponding water surface elevations at the known flow along the waterway at the time of the survey.

An index (a modified desired list) of the cross-sectional channel geometry should be prepared in the field and should not rely on x,y,z data recorded in the survey instrument. The index cross section descriptions should correspond to features showing up topographic quadrangle maps if possible to facility processing in the office. The following is an example of such an index. The exact mileage below the dam is determined by the survey crew. Cross section pencil marks on the aerial photographs and the topographic maps are approximate. The survey crew should locate the hydraulic controls (high points) and the bottom of the pools which is best determined in the field. The following is an example of a desired index of cross section locations and descriptions which help the modeler locate cross sections when looking at a topographic map:

Cross Section No.	Approximate River Mile Below Dam	Description
1	0.010	in pool about 25 ft below conduit outlet
2	0.050	spillway centerline (widest part of the pool)
3	0.100	in pool 125 ft upstream of weir (+weir height)
4	0.101	in pool just below the weir
5	0.250	in pool just below bridge
6	0.300	hydraulic control of pool before wide riffle
7	0.700	in pool before riffle (elevation 6640) and close to branching road
8	0.850	hydraulic control of pool close to road
9	0.900	below control before bend by cliff
10	1.100	in the meandering deepest portion of pool
11	1.300	end of meander in wide part before the bend and in the pool
12	1.600	in the bend pool with wide gravel
13	1.800	in the next bend riffles on the hydraulic control
14	2.050	in bend on island head near contour 6620 ft
15	2.200	end of the steep section

16	2.600	on hydraulic control where road strays away from the river
17	3.000	near farm road on steep slope
18	3.400	on control before waterfall
19	3.500	in shallow pool one tenth of mile below weir
20	4.100	on control just before bend and tributary
21	4.700	on hydraulic control where canyon enters
22	4.800	on hydraulic control in bend
23	4.950	in the deepest part of bend, contour 6580 ft
24	5.350	in pool in new loop
25	5.800	in pool before new cutoff
26	5.950	on head of island before braiding, angle the cross section in an L-shape
27	6.500	in pool downstream of braiding
28	6.700	in pool upstream of small control
29	7.100	in meanders of new cut off
30	7.500	below lone dome after trib from reservoir
31	7.900	in pool below hydraulic control
32	8.100	in pool before hydraulic control
33	8.500	in pool of bend near road
34	8.700	in pool after bend
35	9.100	in pool just before hydraulic control
36	9.400	in pool on bend
37	9.600	in pool below rocks
38	10.050	in pool before hydraulic control
39	10.500	in pool before bend close to road

40	10.700	in mid-pool deepest part
41	10.800	in pool before hydraulic control
42	11.200	in pool before hydraulic control
43	11.400	on the hydraulic control
44	11.700	on hydraulic control before the bend
45	12.100	in pool before bridge
46	12.500	same point as temperature gage