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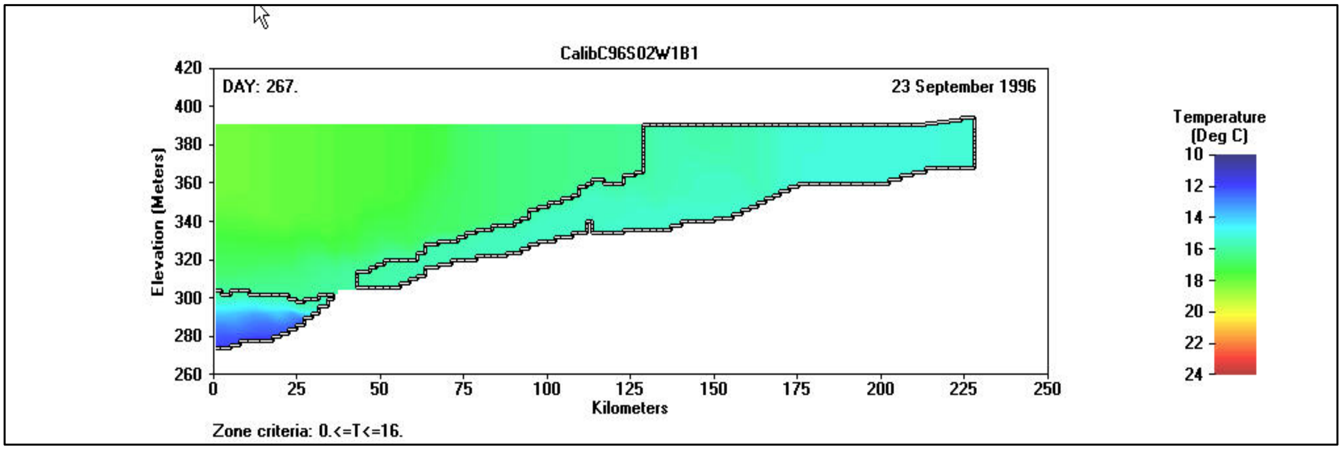
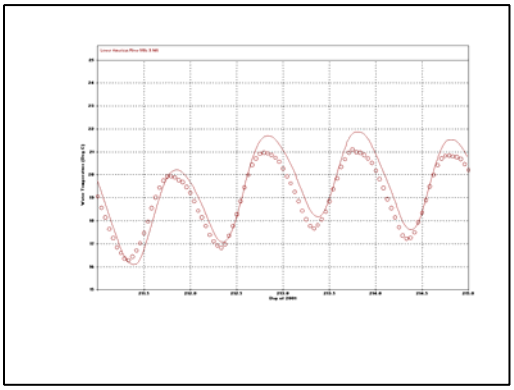
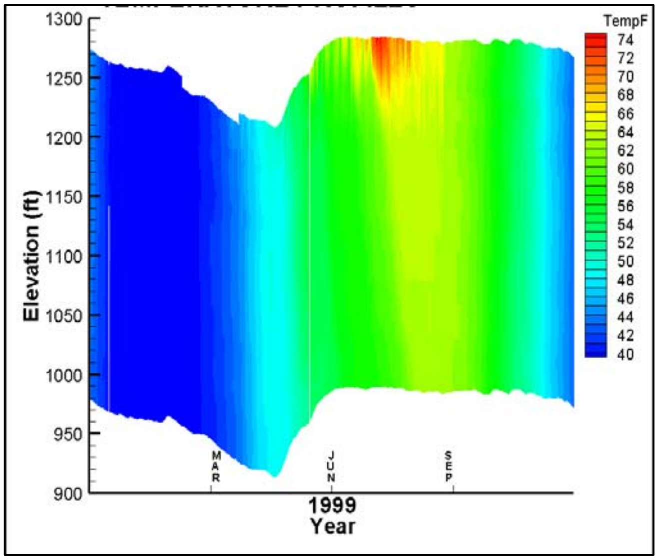
Manuals and Standards

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, Colorado

May 2009

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

There is room for water quality model calibration improvement. Much of that improvement can be tied to the Sampling Analysis Plan (SAP), which describes the type of data, as well as when, where, and how often data are collected. Water quality model calibration is an evolving art and is not based on a rigid set of input parameters. Selecting a model, developing SAPs, collecting accurate and useful data, modeling, and writing the report is a costly and time consuming coordination effort that requires quality assurance and understanding at all levels. However, the modeler is ultimately responsible for the quality of the final project report; therefore, it is necessary to communicate what is expected for data sets that can be used for modeling.

The primary goal of modeling is to reduce error at every step of the process. Errors enter into the SAP design, data collection, lab analysis, data processing, model formulation, input formulation, numerical computations, model calibration, interpretation of results, and reporting. Summarizing and averaging information causes loss of detailed information and meta data describing the data quality.

The many details of collecting data correctly cannot be covered in a single document. These guidelines touch on some important data collection problems that exist for reservoir water quality models which focus on algal productivity and organic matter decomposition. To alleviate data collection problems, recommendations are provided.

Six Data Collection Recommendations for Reservoir Water Quality Modeling

There are six important input data recommendations for modeling algal productivity, organic matter decomposition, and dissolved oxygen (DO) in thermally stratified reservoirs. These are discussed below.

Collect Water Samples for Orthphosphorus (Soluble Reactive Phosphorus)

The most important parameter for reservoir water quality models used to simulate algal growth is soluble reactive phosphorus (SRP) meaning ortho-P (PO4-P). Most phosphorus total maximum daily load (TMDL) studies focus on total phosphorus; however, that is not what goes in most models. Therefore, it is necessary to filter samples to separate the particulate phosphorus. Parameters such as total phosphorus, total dissolved phosphorus, total inorganic phosphorus, and dissolved inorganic phosphorus can be used during model calibration;

however, these parameters are not typically used directly as model inputs. Reservoir dissolved oxygen models require bioavailable phosphorus that is readily taken up and used by algae. In nutrient-poor oligotrophic lakes and reservoirs where soluble reactive phosphorus is minimal, algae may take up more of the total phosphorus. In such cases, a combination of total phosphorus and soluble reactive phosphorus data may be used to formulate inputs to the models. Information about a reservoir's trophic condition should be factored into the data collection plan. Sampling oligotrophic lakes and reservoirs may require a low-level detection protocol and laboratory that specializes in low nutrient concentrations to avoid many below-detection-limit values resulting in minimal useful data.

Collect Profiles Early Spring and Late Autumn

Initial conditions are extremely important to reservoir modeling; therefore, it is important to begin collection prior to the onset of stratification. Modelers typically prefer to start the model on either January 1 (day 1), March 1 (day 60), or March 31 (day 90), depending on stratification. Unfortunately, most reservoir models start on the first day data was collected in the calendar year. Starting data collection after the onset of thermal stratification tends to minimize the use of the entire year of data. A primary concept of reservoir modeling is to reproduce the mixing mechanisms adequately and to verify the ability to predict the timing of reservoir stratification and destratification by model calibration to temperature and DO profiles. Wind mixing events that break down reservoir stratification tend to occur during early spring and late autumn due to weak thermal stratification. Models that end in early autumn miss autumn destratification (fall overturn). Important processes such as fall algal blooms can affect DO concentrations into late autumn and early winter and often are the reason for low DO concentrations caused by algal die-off.

Collect Organic Decay Data

Labile dissolved organic matter (LDOM), refractory dissolved organic matter (RDOM), labile particulate organic matter (LPOM), and refractory particulate organic matter (RPOM) are necessary daily inputs to the CE-QUAL-W2 (W2) model, a common industry standard model. Dissolved organic matter (DOR) and detrital matter (DET) are required daily inputs to the Box Exchange Transport Temperature Ecology Reservoir (BETTER) model, a simpler model. These inputs are difficult to derive without biochemical oxygen demand (BOD) data. Five-day BOD (BOD5) information is required for most models. BOD data should be collected on all major inflows to the lake. If a contract laboratory does not run BODs, it should be analyzed at a nearby wastewater treatment plant.

Collect Total Inorganic Carbon (TIC) and Alkalinity (ALK) for pH Calculations

At least monthly, reservoir temperature, DO, conductivity, and pH, from the onset of spring stratification through autumn destratification, are required for calibration. The pH is not an input to some reservoir water quality models such as W2; however, it is used to check the modeled reservoir pH profiles and the increase in algal biomass. Both W2 and BETTER need daily TIC, ALK, and pH data as inputs or calibration data.

Collect at the Model Layer Centerline Depth from Surface

Collect profiles using the same depth increment as the "centerline" of future model layers to save large amounts of time and improve model accuracy. The W2 model is an internationally recognized model that uses metric inputs and outputs and typically uses 1-meter layers. Therefore, for 1-meter layer W2 models, sampling should be done at 0.5 meter, 1.5 meters, 2.5 meters, and so forth, below the water surface ensures that observed (field collected) data are plotted at the "centerline" of the model layer and facilitates absolute mean error (ABS) and root-mean-square-error (RMS) closeness-of-fit statistics as shown in figure 1. For figure 1, the modeled data appear to be statistically within 1 degree Celsius (°C) of the sparse field data in this deep reservoir. Often, data are collected at the surface and 1.0-meter depth increments from the water surface to the bottom. However, 1.0 meter is at the interface between the layers of a 1-meter layer model, rather than at the centerline. Collecting data at the centerline of each modeled layer could improve calibration statistics or reveal concerns. Setting up automated continuous sampling (for instance, thermistors strung from the water surface to the bottom of a reservoir forebay collecting data every 10 minutes) further improves accuracy and saves data processing time. Taking the mean of data collected at layer interfaces after the data have been collected is not recommended, as it introduces error, and is time consuming. The BETTER model uses English units and, typically, 5-foot layer thicknesses. Therefore, if a BETTER model was to be used (rare these days, since W2 is much more commonly used), the centerline of a 5-foot layer is 2.5 feet. As the different models have different data requirements, a model should be selected before data collection begins.

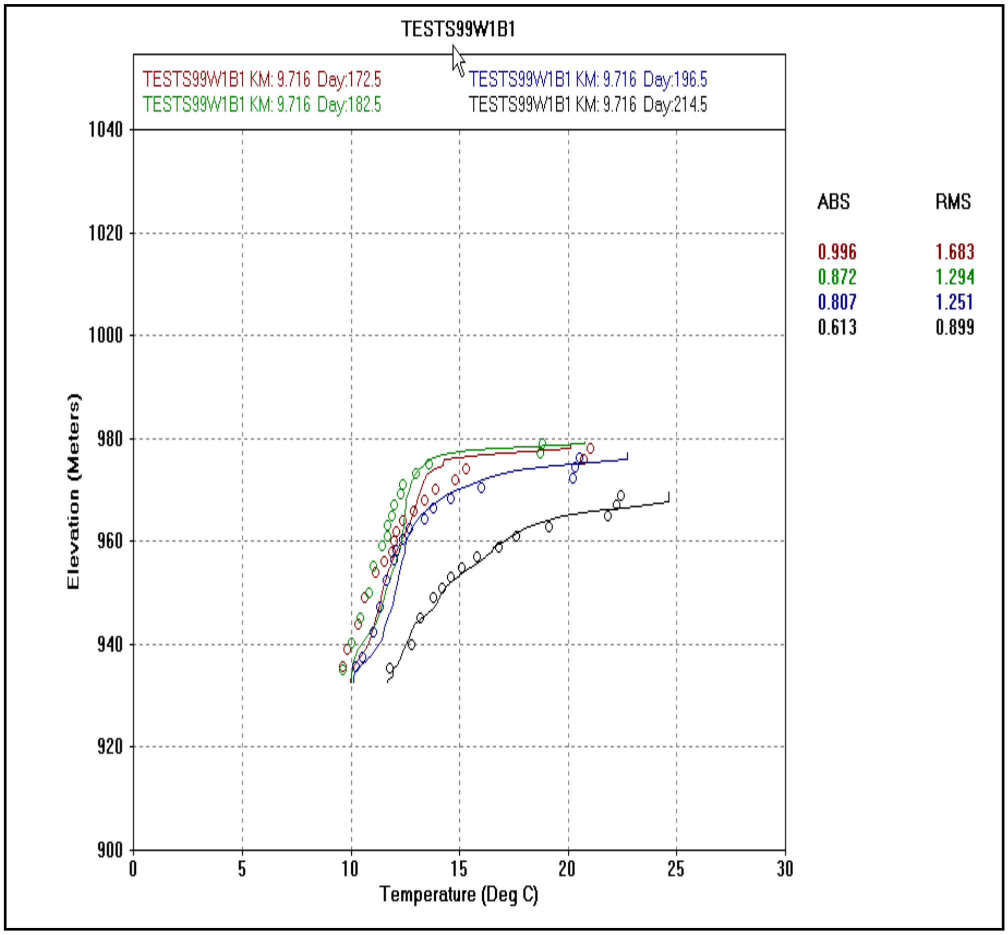

Figure 1. Example of closeness-of-fit statistics between model (line) and observed (circles) reservoir profile data.

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 branches, layer depth, longitudinal segment size, and tributary inputs to model segments).

Choosing the model to be used before data collection allows for collecting 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 reservoir inflow area that dries up, or drops to a lower level than incoming tributary branches, may cause a fully hydrodynamic model to stop during numerical simulation. Resulting adjustments could be made to the model construct or branch and tributary formulation that might alter where samples are collected. It may be necessary to model deep stagnant embayments as separate branches. The chosen model, and model construct, 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.

What is Covered in These Guidelines?

The following guidelines were written with an emphasis on water quality data collection and two-dimensional (2D) modeling of reservoirs. Data collected for riverine models differ and might be covered in a separate document.

Several types of data are required for reservoir modeling. Model geometry (bathymetry developed from contour data), initial conditions (before stratification), inflow water quality at the mouth of and in major inflows (including local inflows), water quality in the reservoir (profiles), multi-level outlet information, branch and tributary inflows, dam and withdrawal outflows corresponding to system-wide and selective-withdrawal operations, dam release water quality, and meteorological data are typically required.

Reservoir simulation modeling is described using the typical pattern of reservoir DO model calibration. Reservoir topographic or bathymetric data are required to build the numerical container for the model. Flows in and out of the reservoir are needed for a water mass balance calibrated to water surface elevations. Reservoir operational data are required for modeling flow water mass balance and selective withdrawal from different vertical levels. Meteorological data are required to replicate stratification patterns. Stratification is modeled to establish a medium for longitudinal interflows based on density. Water quality data are then added to the model to simulate algal growth and organic matter composition or degradation.

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 ensure this does not happen. A few model calibration data sets, in combination with sensitivity analysis, often provide great insight into what makes a reservoir tick and how to alter operations for in-reservoir and release water quality improvements.

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

1.0 Application

Well-calibrated numeric reservoir water quality and hydrodynamic 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 network that accurately represents the reservoir system characteristics. To capture varying water quality from dry to wet conditions, reservoir water quality modeling data require planning and data collection several years in advance.

The primary application of the following guidelines is for data collection supporting a W2 reservoir model or similar fully hydrodynamic, 2D, laterally averaged water quality reservoir model. Appropriate planning for environmental data collection and processing is critical to overall success in developing accurate reservoir predictive simulation capability.

1.1 Purpose and Scope of Guidelines

These guidelines address critical data necessary to support W2, a widely recognized and well-proven numeric 2D reservoir 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 W2 modeling theory or technical instructions, such as those provided by Cole and Wells (2002 and 2006, http://www.ce.pdx.edu/w2/. These guidelines are intended to provide insight into factors involved in data collection for W2 for typical Bureau of Reclamation (Reclamation) reservoir 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, revised August 2003). The "Quality Assurance Guidelines for Environmental Measurements" provide templates in many areas of the planning and data collection process. "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 data including:

- Glass or plastic?
- Instrument calibrations?
- Sample holding times?
- Duplicates, blanks, rinsate blanks, replicates, splits, spikes, lab round-robins, and references?
- Half meter, one meter, five feet, surface, grabs, 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

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

1.2 Role of Reservoir Simulation Models in Water Resources Planning

Reservoir water quality and hydrodynamic modeling capabilities, such as calibration to wet, normal, or dry years for simulating (computing) over a range of conditions, are developed using measured input data that reflect defined (historic) conditions. The model uses these data sets to accurately simulate processes governing hydrodynamic and water quality conditions in the reservoir.

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 reservoir conditions during drought, model calibration should incorporate data collected during dry years.

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 reservoir models can accurately represent a range of hydrodynamic and water quality processes. For example, a competent simulation model, such as W2, could help predict the dynamic effects of operational or structural changes on thermal stratification or interflows within the reservoir, 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 reservoir. 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), 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.

Table 1. Water Quality Models

Model Name/Acronym	Short Description	Scale
ADYN-RQUAL	Unsteady state hydrological model of water quality for use in rivers (river modeling system (RMS))	Riverine
AGNPS/Ann-AGNPS	Agricultural Non-Point Source Pollution Model - annualized version of AGNPS	Watershed
ANSWERS	Areal, Non-Point Source Watershed Environment Response Simulation - watershed response	Watershed
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources - water quality	Watershed
BATHTUB/FLUX/ PROFILE	U.S. Army Corps of Engineers empirical eutrophication response model in lakes and reservoirs	Reservoir
BETTER	Box Exchange Transport Temperature Ecology Reservoir model - 2D water quality model for reservoirs	Reservoir
CE-QUAL-W2	U.S. Army Corps of Engineers water quality model for reservoirs - 2D	Reservoir Riverine
CAEDYM with DYRESM or ELCOM	Computational Aquatic Ecosystem Dynamics Model run with hydrodynamic model DYRESM or ELCOM	Reservoir
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	Riverine
HSPF	Hydrological Simulation Program - FORTRAN data intensive hourly input water quality program	Riverine
HYDROSS/CRRSAP	Hydrologic and water quality 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	Any water
QUAL2EU	Enhanced stream water quality model with uncertainty analysis for well-mixed streams	Riverine
RIVERWARE	System-wide operational model	System
SWMM	Storm Water Management Model - water quality analysis for urban runoff	Watershed
WASP5	Hydrodynamic river water quality model - eutrophication, metals, and toxics	Riverine
WARMF	Watershed Analysis Risk Management Framework – stakeholder daily watershed planning model	Watershed

2.0 Reservoir 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 or reservoir 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 large differences between input scenarios.

Reservoir 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, reservoirs with peaking-power operations require 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 model development approach. 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.

2.1 Different Types of Reservoir 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 modeling runs can provide valuable information.

Different types of models are designed to serve different purposes. For example, 1D reservoir models (completely mixed over an entire layer from inflow to outflow) are limited because the longitudinal gradient is not modeled. By contrast, 2D models such as W2, that support vertical and longitudinal gradient hourly simulation, can be used for selective withdrawal investigations, interflows through reservoir layers, or other structural and operational alternatives. Using a fully hydrodynamic 3D model is computationally intensive, typically results in quasi-steady state assumptions, and can result in modeling only a portion of a reservoir, which limits the usefulness of the findings. 3D models also can involve a great deal of time and money spent on collecting data, which may not provide better and more accurate simulation results than a 2D model. For example, a 3D dam forebay model using a quasi-steady state upstream boundary condition may not simulate internal seiching (sloshing), as defined by Wetzel (2001), near the dam and may miss dominant hydraulic and thermal dynamics. A fully hydrodynamic model, such as W2, which incorporates seiching (sloshing) may be a better choice for the seiching scenario described.

Additionally, accurate model calibration may require extensive construction. 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 2D model is a compromise between simpler 1D modeling versus increasing data and computation requirements. A 2D model approach can handle reservoir conditions that vary vertically with depth or longitudinally through the reservoir. A 2D model allowing dynamic branches approaches a quasi-3D capability. This minimum capability is essential to examine processes such as thermal stratification or interflow currents found in many reservoirs and their tributaries. Simulations requiring varying longitudinal gradients are not possible with a 1D model. A 3D model requires extensive data sets to express how conditions actually vary laterally, longitudinally, and vertically. 3D models also require additional resources for model development, data management, computation time, and output analysis. By contrast, a well-defined, fully-calibrated 2D model, such as W2, can provide a cost-effective means to simulate hourly, daily, seasonal, and annual operative conditions in reservoirs while addressing interrelated water management questions.

2.2 CE-QUAL-W2 as an Industry Standard

The thoroughly tested W2 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 reservoirs. Version 2 of the W2 model (USACE, 1995) has been upgraded extensively.

Recent versions of the W2 model have several upgraded pre-processors and post-processors to accommodate changing user needs. Extensive use of CE-QUAL-W2 generated reservoir profiles is possible through the Animator Graphics Portfolio Manager (AGPM) for presenting a single day in combination with 2D contour animations during the calibration process. Such error checking, color animations, goodness-of-fit statistics for calibration, enhanced plotting, and many other features save modelers effort and time calibrating, preparing, and presenting information. For example, a depth versus day contour plot (constituent on contour) is typically plotted at the inflow, at mid-reservoir, and at the dam for a seasonal picture of the entire reservoir for observed or modeled data. Additionally, multiple daily color animations (contour plots through time) of several parameters at several locations provide a powerful learning tool for quickly analyzing extensive data sets of a reservoir.

The W2 model is a fully hydrodynamic model which uses the equations of mass and momentum to calculate hydraulics. Inflows, outflows, surface winds, and internal seiching can all affect the flow patterns within a reservoir, lake, or stream system modeled with W2. The W2 model geometry consists of widths, lengths, and thickness of each cell. Each cell's water volume is calculated every iteration. Recent versions of W2 can be used for a broad variety of situations such as multiple water bodies including linking of riverine and reservoir water bodies. Steep shallow riverine stretches can be modeled with one layer. W2 Version 3.1 (Cole, T.M., and S.A. Wells, 2002) and newer versions include the following features:

- Total dissolved gas (TDG) - added capability for TDG simulation
- Algal groups - supports any number of defined algal assemblages
- Density gradients - salinity effects on hydrodynamics in water quality module
- Long-term simulation - larger time steps for long-term water quality processes
- Multiple branches - can accommodate multiple tributaries and branches
- Multiple waterbodies - can be applied to linked rivers, reservoirs, and lakes in series
- Variable grid spacing - allows variable segment lengths and layer thicknesses

- Selective withdrawal - options to restrict vertical extent of withdrawal zone
- Time-varying conditions - allows a set of independent time variable inputs
- Output processing - significant development of enhanced output capabilities

Version 3.11a of W2 has been tested extensively and has few coding bugs. Version 3.11a has enough functionality for most applications. In addition, the CE-QUAL-W2 Version 3.1 users manual (Cole, T.E., and S.A. Wells, 2002) 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 reservoir conditions. The more recently released and more feature-laden version of W2 is version 3.5, which works well with AGPM version 3.34. W2 model version 3.6 is in beta testing. Newer, less-tested versions of W2 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 W2 model to predict hydrodynamic, thermal, and water quality changes has allowed it to become a favorite tool among modelers and an industry standard. W2 has replaced previously used 1D models such as the CE-QUAL-R1 model (U.S. Army Corps of Engineers (USACE), Environmental Laboratory, 1982) or the 2D BETTER model (Bender, et al., 1990). This favorite tool, coupled with innovative approaches to capturing 3D effects by using dynamic branches or varying selective withdrawal calibrations, has been successful at cost effectively modeling numerous scenarios.

2.3 Major Physical and Biochemical Processes

Some of the major physical and biochemical processes modeled by the BETTER model, as well as the W2 model, are shown in figures 2 and 3.

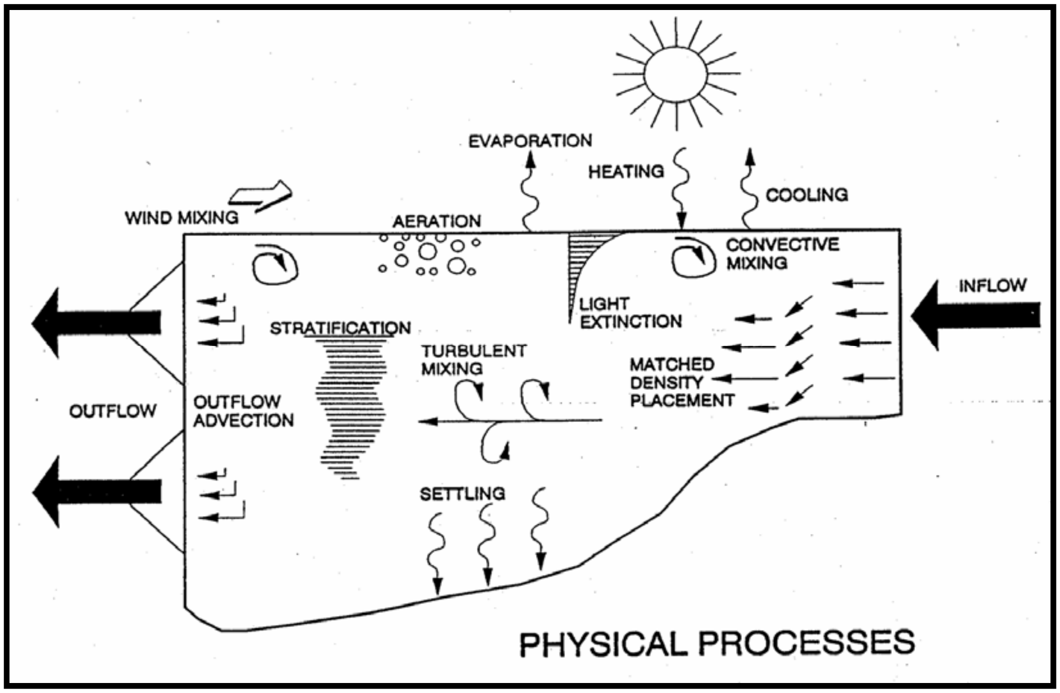

Figure 2. Major physical processes modeled by Better and CE-QUAL-W2 (Bender, et al., 1990).

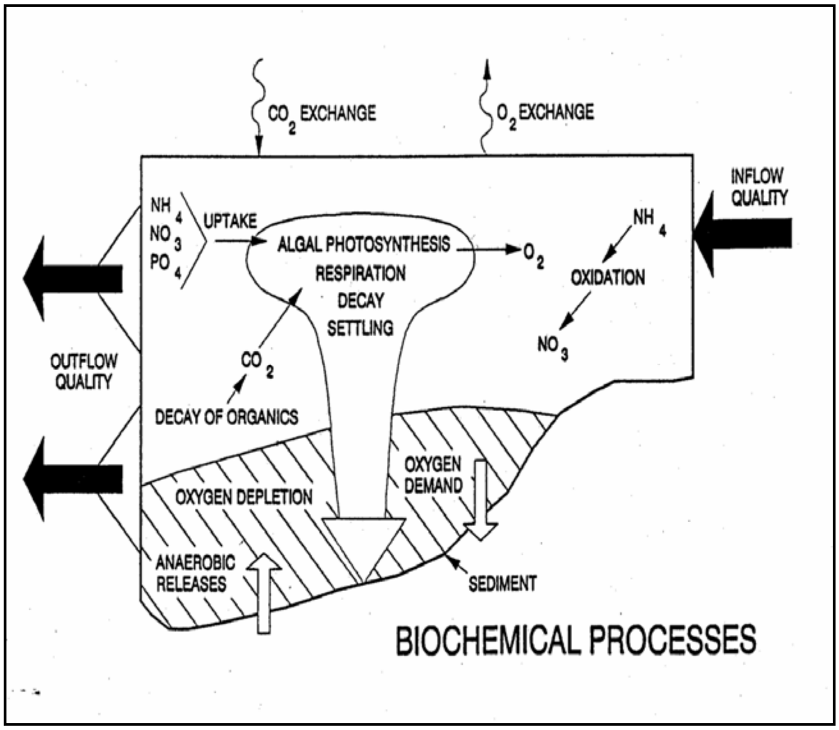

Figure 3. Major biochemical processes modeled by BETTER and CE-QUAL-W2 (Bender, et al., 1990).

2.4 Simulation Model Data Requirements

Numeric computer models created to simulate dynamic reservoir 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 reservoir. Complete sets of meteorological, water quality, and hydrologic data at the appropriate daily or hourly time intervals are required for all years used for initial model calibration. In addition, accurate measurements of physical dimensions, dam outlet configuration, and operations data are required to represent controlling conditions for the reservoir-specific model. As-built design drawings and “Project Data Web” (Bureau of Reclamation, 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 reservoir model, and complete reference data sets for selected years 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, “hourly input” data sets are required for the entire year to capture diurnal effects, hourly changes in meteorology, or peaking-power fluctuations. Daily output data may be more useful for digesting effects of internal seiching, multiyear simulation length, 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 grid designed to capture hydrodynamic, thermal, and water quality constituent gradients. Typically, 1-meter layers, and about 1-kilometer segments, are adequate for reservoir modeling. Shorter longitudinal segments are used at steep inflow areas. Geometry developed by merging aerial and bathymetric surveys, which capture the contours and embayments around the reservoir, are recommended over cross-sectional channel surveys that may miss small embayments and cause underestimation of reservoir volume. Hourly data are typically required for intermittent peaking-power or other intermittent pumping operations affecting inflows or outflows to the reservoir. Inflows, outflows, inflow temperatures, outflow temperatures, meteorology, and reservoir temperature profiles are required to capture daily water mass balance and seasonal thermal gradients for model hydrodynamic calibration. Continuous completely-mixed temperature of the combined dam discharge, individual outlet flows, and continuous dam forebay temperature profile information is useful for selective withdrawal calibration.

2.4.1 Reservoir Physical Configuration and Computational Grid

Accounting for hydraulics, such as interflows shearing past near dead-storage embayment branches, during model construct and water mass balance computations is critical in developing fully functional, accurate simulation capabilities. Major factors include an accurate reservoir stage-volume curve, defined by the bathymetric mapping used in the model computational structure, and the inflow and outflow data sets for all major branches and outlet points. Accurate bathymetric data, including that in deep tributaries to the reservoir, is required to represent the hydraulic flux governing temperature and other reservoir processes. Complete calendar year inflow and outflow data sets are necessary for calibration years and the base reference year used in model simulations.

Vertical layers are typically defined as 1-meter increments from the surface, and bottom layers can be greater, depending on minimal vertical stratification (see figure 4 from Cole (1994)). The left side of figure 4 is Cole’s figure 10-1; the right side is Cole’s figure 10-2. In the left temperature profile sketch, the curve for adsorption of light (“A”) is very different in shape from the curve depicting the deeper vertical temperature profile (“B”). The figure on the right illustrates the three temperature layers in a thermally stratified lake. The epilimnion is the warm surface water characterized by greatest light penetration and turbulent wind-mixed waters. The metalimnion is the transition zone where the rate of temperature change is greatest. The hypolimnion of cold, denser water is at the bottom depths. An isothermal water body is one where temperatures are unchanged from surface to bottom and is common during colder conditions. Density differences caused by salinity and cool interflows can cause abnormal-looking profiles. Fortunately, such conditions can be modeled with dynamic models, such as W2, that have density formulations incorporating both temperature and salinity differences between vertical layers and interflows.

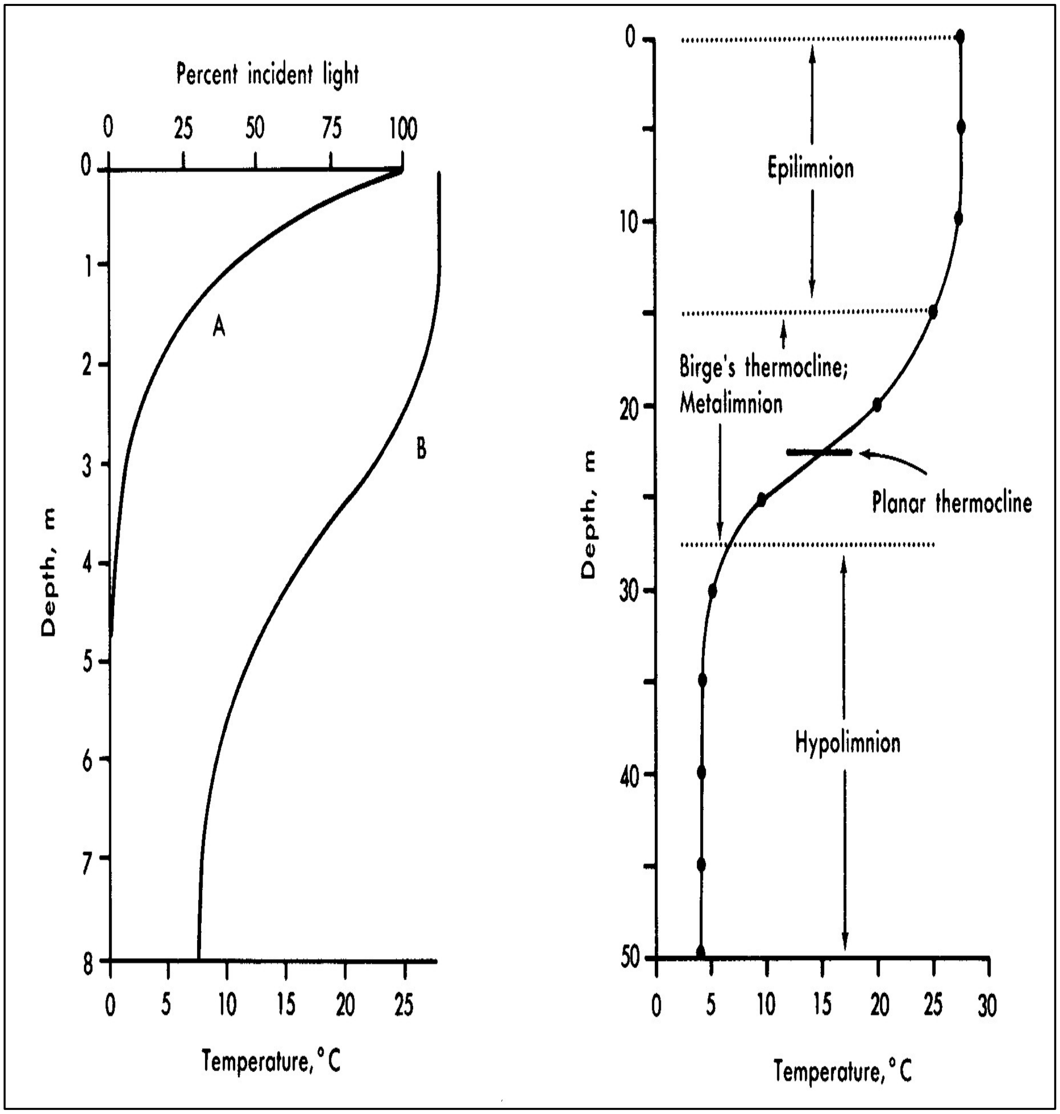

Figure 4. Different temperature profile shapes (left-plot profiles A and B) and typical thermal stratification defined (right-plot profile) (Cole, 1994).

2.4.2 Representative Calibration Years and Data

Selecting years to calibrate dry, average, and wet flow conditions is a key factor in developing a reservoir model. Years selected could be based on water years (October 1 of previous year to September 30) or calendar years (if water quality model output is compared to a yearly standard). In many cases, dry years may be of interest; in other cases, wet or average years may be of interest. Other years that may be of interest include the highest water year on record, a hot year in terms of the ambient air temperatures, years in which mean streamflows are close to the minimum water year, a median water year, and a year with the annual mean streamflow conditions. 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 better hourly inflow water temperature and meteorological data for use in reservoir 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.

Overall, it is better to construct a reservoir model using fairly recent years of hourly data, and several years in sequence could allow multiple year simulation. Such a challenging single run and single initial condition approach is a potential advantage for more efficient model calibration. However, model temperature drift must be checked against observed data for each calibration year simulated if possible.

2.5 Model Calibration and Testing

An initial series of tests are conducted on the calibrated reference 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 feasibility of potential aspects of water quality management options. The main goal of sensitivity analysis is to identify major operative factors and to formulate specific scenarios or alternatives for more detailed investigations.

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 and 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. 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.

2.6 Other Model Data Collection Considerations

Model development should also consider methods to expand capabilities as necessary to integrate other water quality parameters. For example, TDG problems are tied directly to reservoir spilling, so detailed reservoir modeling may not be necessary to evaluate remediation alternatives. However, internal process modeling may be useful to evaluate transport and TDG effects within a reservoir. In addition, since alternatives to manage TDG could also influence other processes, the ability to combine temperature and TDG simulation in one model may have advantages. These factors can affect the model development approach considerably.

The latest version of W2 offers advantages in terms of the available simulation capabilities, continued development and support, 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 limnological characteristics and to evaluate different structural or operational alternatives for water quality management. These capabilities could also be used to provide more detailed testing of coordinated data collection and management in a basin by several agencies.

In summary, successful modeling projects require extensive planning for model selection, data collection, sample processing, archival, analysis, presentation of results, and interpretation that support the data quality objectives (DQOs) and QA plan. 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:

> (1) 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.
>
> (2) Bureau of Reclamation, September 2003. "Technical Guidelines for Water Quality Investigations. U.S. Department of the Interior.

3.0 Reservoir Topographic Data

Reservoir topography and bathymetry are used to develop the computational grid. The physical geometry controls the hydraulic properties represented, which influence many associated reservoir water quality processes. Topographic data are used in 2D models to develop a grid of cells for numeric computations.

Several methods are used for collecting reservoir geometric data (Ferrari and Collins, 2006). Merging a flown aerial coverage, such as Light Detection and Ranging (LIDAR) coverage taken at a low pool and a bathymetric coverage taken at a pool high enough to overlap the flown coverage, can produce accurate geometry. This approach requires adequate software and technical expertise. Typically, dikes or saddle dams are estimated and added to the top impoundment water surface to provide extra space for looking at a potential "raise the dam" scenario or for facilitating a water mass balance on full-pool historical data that may overflow the modeled container before correcting for errors in the water mass balance. The resulting merged coverage can be quite large, with millions of data points. Overly large data sets may require a software package that compresses the data set without losing accuracy. It may also be necessary to eliminate bad data points due to trees above the water surface or submerged rocks and weeds. A triangular irregular network (TIN) is produced and clipped at the surface. That clipped TIN is then transferred to Environmental Modeling Systems, Incorporated (EMSi) software, where the reservoir can be sliced into cells in W2 format. This can be an iterative geometry calibration process to a known area-capacity curve verified from years of water mass balance information using several Geographic Information System (GIS) methods. After slicing the reservoir into layers and longitudinal segments, it may once again be necessary to reslice the longitudinal segments, depending on potential problems with the geometry that may cause stability problems. Accurate geometry is likely the single most important component of reservoir modeling. Many errors and inadequate water quality calibrations can often be traced back to poor geometry development techniques.

3.1 Alternative Reservoir Topographic Data Sources

Cursory assessments with limited funding may use cross-sectional channel geometry and other rough topographic data sources. Existing model geometry, cross-sectional channel geometry tied to a vertical datum, area-capacity curves, 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 bathymetry can be developed.

3.2 Reservoir Bathymetric Survey Mapping Methods

Accurate reservoir surveys include an aerial coverage taken at low pool and bathymetric coverage taken at high pool. These two geometric surveys are merged and then processed.

Bathymetric surveys use sonic depth recording equipment interfaced with real-time kinematic (RTK) and global positioning systems (GPS) capable of determining sounding locations within the reservoir. Horizontal coordinates of the survey boat and depth are continuously recorded as the boat is navigated along grid lines. The positioning system provides information to maintain a course along the grid lines. Stationary differential GPS is typically used to improve accuracy of the moving survey.

Aerial coverages derived from georeferenced LIDAR data, in conjunction with a full reservoir contour digitized from a topographic map, are typically used to extend the bathymetry higher than the actual dam. A higher modeled reservoir allows for slope storage during modeling of flood events and provides a cushion for developing water mass balances that initially overfill the reservoir before corrections are made to inflows.

3.3 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 North American Vertical Datum of 1988 (NAVD88). All coordinates are tied to a horizontal projection. Units for vertical and horizontal datums may be different and need to be converted to similar 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.

3.4 Model Computational Grid Considerations

How reservoir physical geometry is converted into computational segments in the model depends partly on available data, model approach, and professional judgment. For example, layers above the hypolimnion may be represented by 1-meter thickness, and those in the hypolimnion as 2-meter (or greater) thickness. Vertical layer thickness depends on the resolution of the underlying bathymetric data and can be adjusted to consider the run time for model iterations and testing trials of large reservoirs. To ease confusion and simplify modeling, 1.0-meter layers are typically chosen throughout the reservoir column.

The horizontal (plan view) breakdown should include inflow and outflow points designed to represent the reservoir mainstem and tributaries. The last model segments at the dam forebay might be adjusted to reflect islands in the forebay and underwater structures that restrict withdrawal of water. 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 reservoir geometry 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.

There is often a tradeoff between the number of computational elements and the computation run time and stability of a hydrodynamic model. There also may be certain areas in the reservoir in which mixing and stratification properties are more dynamic and critical to represent in a model. For example, deeper zones near the dam forebay, tributary inlets, or locations where cross-sectional geometry changes significantly could affect hydraulic characteristics (e.g., vertical mixing or longitudinal flow patterns).

4.0 Flows and Water Balance Data

Data representing major water inputs and losses from the system are required for hydrodynamic reservoir modeling. This refers mainly to flow and stage data, because precipitation, seepage, and evaporation are derived from meteorological data or included in the local drainage calculation. Adequate flow data are necessary to set up the model water mass balance for selected water years or calendar years that represent a range of conditions (e.g., dry, average, and wet) for model testing. In addition, measurements of reservoir water surface elevations are also necessary for water budget calculations.

There are several methods of developing a water mass balance for individual reservoirs as well as a system water mass balance with more than one reservoir. Typically, known inflow and outflow information, in conjunction with reservoir 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 year to year. After geometry, an accurate water mass balance is critical for estimating flushing 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. This often requires conversations with field personnel who maintain the gages and collect the data.

Typical mistakes include collecting reservoir profiles either upstream or downstream of an abandoned cofferdam or debris wall on different sampling trips. Another mistake is to implement a thermistor string on a buoy near the dam downstream of a thermal barrier structure. Internal seiching (sloshing) has a significant fluctuating effect on temperatures collected near the dam. Figure 5 (Bender, et al, 2007) depicts the significant temperature differences upstream and downstream of underwater barriers for an assumed quasi-steady state condition.

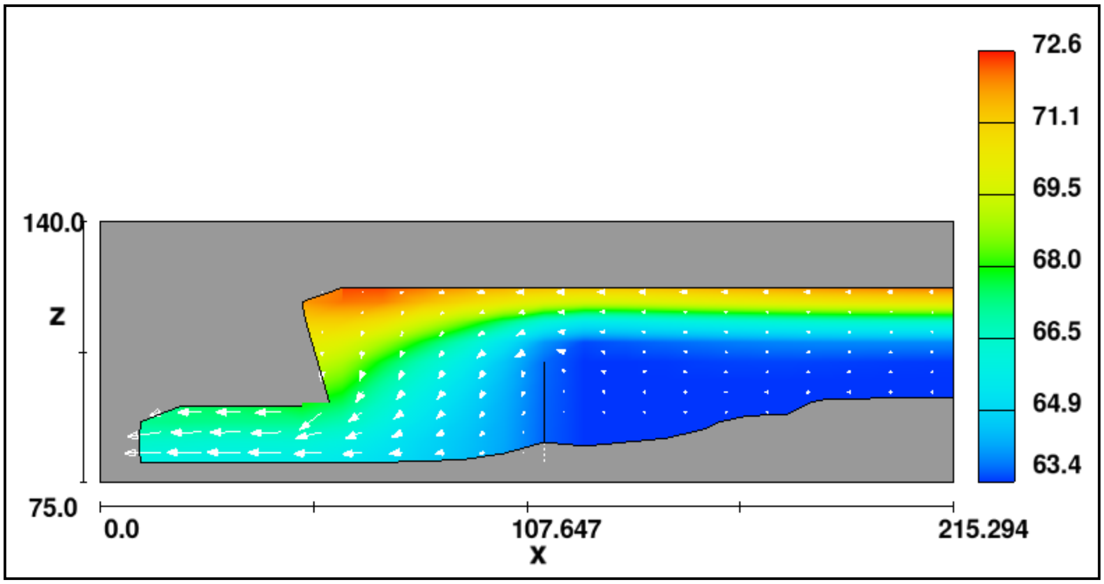

Figure 5. Temperature contours upstream and downstream of a debris barrier wall in near-field of powerplant intakes into a dam (flow direction is right to left). The color contours represent temperature (in degrees Fahrenheit (°F)), x and z distances are in feet, and vectors represent resultant velocities (Bender, et al, 2007).

4.1 Reservoir Water Mass Balance Data Sources

The methodology for a water mass balance should be tailored to the reservoir based on known inflow and storage information. Inflow from ungaged tributaries will need to be estimated from nearby streams using correlations or factored into the combined unknown error and local-drainage inflow component. In some cases, it may be best to apportion some of the error to reservoir outflows. Pump storage operations may add another layer of complexity to the water mass balance. W2 has a water mass balance utility that tries to match water surface elevation over a seasonal or annual basis. Water mass balance should be done independently for each year if years 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. Evaporation rates are sometimes accounted for in estimating the inflow record, such as net inflows computed from outflows and water surface elevation for a "historical case" used in a model calibration (Cole and Wells, 2006, Appendix C). If so, the EVC flag for evaporation included in the water budget should be set to "OFF." However for simulation of future alternatives, the EVC flag should, in many cases, be set back to "ON" because evaporation would not likely be included in water mass balances for alternative simulation. A common mistake is to forget to set the EVC flag correctly or to misunderstand the application of the model after calibration for some future simulation.

4.2 Flow Monitoring and Data Compilation

Accurate readings of actual reservoir water surface elevation without drawdown or stuck gage effects are important. High intake rates near the stage gage or sloshing on the dam face due to wind induced or momentum induced surface water movement may have a large affect on water mass balance since the stage gage measuring water surface is sensitive to small changes in elevation, especially on large water bodies. A stick in the stilling well at low water surface elevation can cause incorrect readings that are off by several meters. Large incorrect readings may need to be corrected with reverse engineering using the model water mass balance as a starting point. Also, some initial model testing could help to evaluate effects of high turnover rate on the model water mass balance and computational stability.

Reservoir models are ideally calibrated to data sets representing wet, average, and dry water or calendar years 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 or supplemented with additional years of data collection. Recent data would incorporate recent operational and structural changes which may affect modeling results. 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 years for the period of record. Consecutive calendar years of wet, average, and then dry years or of dry, average, and then wet years would represent an ideal modeling data set. Calibration years may also be selected based on hot or cool average air temperature years, depending on the expected application.

4.3 Water Budget Data Gaps and Model Considerations

Long-term flow records for mainstem 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 effect model development. In addition, flow data should be examined with respect to reservoir operating conditions and water surface elevations. Some preliminary steps include the following:

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

(2) Conduct preliminary analysis of historic flow records to determine representative dry, average, and wet water years for model calibration and evaluate scenarios or action alternatives.

(3) Evaluate 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 reservoir water quality conditions, such as delayed reservoir turnover. Additional consideration for pumpback storage operations may also need to be incorporated.

5.0 Reservoir Operations Data

Operations data are not directly required for a simple reservoir model; however, such data are essential to assess 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. Total outflows do not discriminate between conditions such as different intake elevations or mixing in the forebay. Consequently, effective model development should consider normal operating conditions and types of alternatives to incorporate in the model construct. First, the operations data must be in a form that is suitable to allow processing and analysis to identify relationships in model evaluations of defined action alternatives.

5.1 Operations Data Required for Reservoir Modeling

Hourly data are required if there are any peaking power generations, either at outflows or inflows to a reservoir. Acoustic Doppler Current Profile (ADCP) flow measurements may not match flows derived from a system water mass balance and should be used with caution.

5.2 Short- and Long-Term Reservoir Operational Factors

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

Often, historical operations data are only available on hard copy and in hand-written form. Operations data tables often include hourly operations for separate intake, pump-storage, and spillway operations. Manual data entry makes assembling the data time consuming.

5.2.1 Single Water Year Considerations

Model development may involve operational changes that occur within a single water year cycle. For example, operations data for powerhouse, spill conditions, or pump-storage operations could be isolated to examine effects on water quality within the reservoir, in releases, and in tailwaters. 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 water years.

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.

5.2.2 Longer-Term System Operations

Assembling an extensive set of historical operations data of more than 30 years may be necessary in evaluating long-term seasonal patterns in multiyear reservoir storage and release conditions at a single reservoir, and in addressing questions concerning relationships between multiple-basin reservoir components or coordinated operating alternatives plans. Reservoir operations modeling may provide a reference for examining certain system-wide conditions or alternatives. To reiterate, initial model development and planning should consider what types of long-term operational scenarios may be of interest.

5.3 Operations Data Gaps and Model Considerations

Converting data tables into electronic files is the first step in using available operations data. Raw data for individual intakes have to be converted and grouped into an appropriate format. Different criteria may be applied to group and sort data for each modeling study. Sorting through reserved, online, and available (ROA) turbine records can make this a difficult task if information has not been recorded for all generation units.

6.0 Water Quality Input Data

Reservoir water quality modeling requires measured boundary input data, calibration profile data within the reservoir, and combined release data in the tailwater. Water quality data include physical (e.g., temperature, conductivity, pH) and biochemical (e.g., BOD, nutrients) parameters.

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 LPOM, RPOM, LDOM, and RDOM by using some relation to BOD or other test for estimating decay of organic matter.

At a minimum, the following water quality data are needed for a model DO calibration:

(i) Inflow waters data (at mouth of major inflows, pipes, and local inflow) including: flow, temperature, DO, turbidity, pH, alkalinity (as $CaCO_3$), conductivity, Secchi depth in reservoir tributary arm, total suspended solids (TSS), total dissolved solids (TDS), NH_3+NH_4-N, NO_2+NO_3-N, Kjeldahl nitrogen, BOD (5 day for estimating dissolved organics and detritus or dissolved and particulate organic carbon), total phosphorus, dissolved ortho-phosphorus (soluble reactive phosphorus assumed to be completely bioavailable as ortho-phosphate (PO_4)), organic N, TIC, total organic carbon (TOC), and total volatile suspended solids (TVSS) or algal biomass (in milligrams per liter (mg/L)). Hourly, or at least daily, average inflow temperatures on major branch and tributary inflows are important in determining mixing and interflows through a lake and reservoir. Inflows with flow gages should also have temperature gages.

(ii) Reservoir (profile) data including: temperature, DO, turbidity, pH, alkalinity (as $CaCO_3$), conductivity, Secchi depth, TSS, TDS, NH_3+NH_4-N, NO_2+NO_3-N, Kjeldahl nitrogen, BOD (estimated 5 day or estimated dissolved and particulate organic carbon), total phosphorus, dissolved ortho-phosphorus (soluble reactive phosphorus assumed to be completely bioavailable as ortho-phosphate (PO_4)), TVSS, and chlorophyll-a. Field data profiles will be plotted in the same format as model results to facilitate model calibration.

(iii) Dam release or tailwater data including: flow from each outlet, temperature, DO, TSS, TDS, pH, alkalinity (as $CaCO_3$), detritus, dissolved organics, algae, NH_3+NH_4-N, NO_2+NO_3-N, BOD (5 day), total phosphorus, dissolved ortho-phosphorus (soluble reactive phosphorus assumed to be completely available as ortho-phosphate (PO_4)), and TIC. Output from one calibrated W2 model may be used as input into another W2 model; therefore, LPOM, LDOM, RPOM, and RDOM and other inputs to another W2 model should be output from the W2 model being calibrated.

6.1 Temperature and Water Quality Data Used in Reservoir Modeling

Many models are initially constructed to examine seasonal 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 monthly vertical profiles collected in the dam forebay and major reservoir branches, and continuous water temperature in inflow waters and the dam tailwater temperatures, are some of the most useful data. However, a surface-to-bottom thermistor string continuously collecting the dam forebay profiles representative of conditions upstream of submerged barriers (such as a construction cofferdam) should be used for calibration, if possible. Figure 6 shows noon modeled (line) versus observed field (circles) water temperature profiles for a dam forebay during mid- and late-summer stratification. To calibrate dam release temperatures accurately, dam forebay profile calibrations must first be correct. Absolute mean error and root mean square error closeness-of-fit statistics are often used to check the accuracy of a profile calibration. Historical release temperature data can be used to check selective withdrawal calibration at several elevation levels once reservoir stratification has been correctly modeled. Release temperatures at depth tend to track better than surface and mid-depth releases in figure 6. Calibrating to bottom releases only provides part of the picture. Figure 7 shows the same three temperature profiles on one plot. Both figures 6 and 7 have corresponding closeness-of-fit statistics. A and ABS are equivalent, and R and RMS are equivalent in figures 6 and 7. Temperature profiles warm over time and provide information on previous stratification patterns. The effects of temperature differences at the thermocline may appear in releases as reservoir water surface elevation decreases and warmer water is withdrawn from the same outlet.

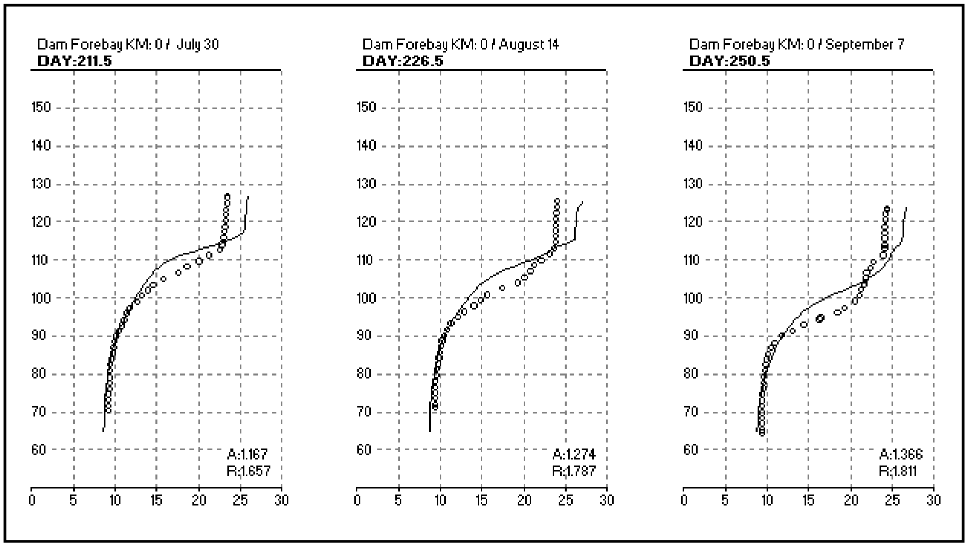

Figure 6. Modeled (line) versus observed (circles) water temperature profile data (elevation in meters versus temperature in °C) in a dam forebay during mid- and late summer. A and R are absolute mean error and root mean square error closeness-of-fit statistics in °C.

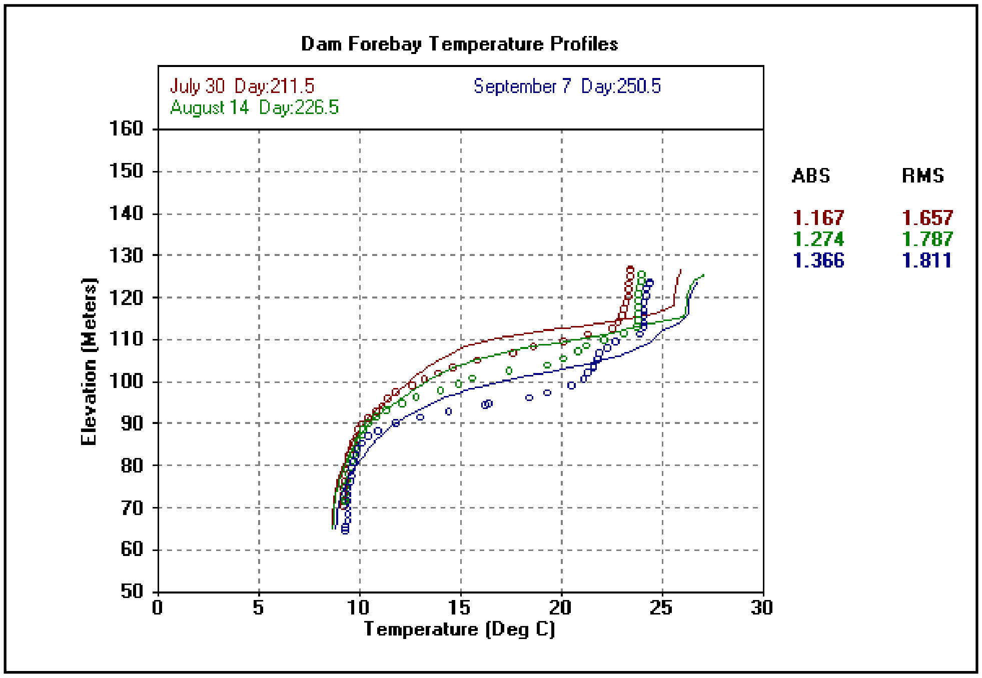

Figure 7. Modeled (line) versus observed (circles) water temperature profiles show changes in mid- to late summer stratification. ABS and RMS are absolute mean error and root mean square error closeness-of-fit statistics in °C.

Salinity data (derived from electrical conductivity (in µmhos per centimeter) or TDS (in milligrams per liter)) are used in hydrodynamic reservoir models to account for density gradients. Fortunately, most instruments used for monitoring include conductance probes. In some cases, it is desirable to use a second water quality parameter in confirming water mass balance and calibration for a reservoir model. For example, DO data can be used in confirming the temperature calibration. Salinity gradients can be useful for showing flow patterns.

Total dissolved gas may also be used in a model limited to periodic reservoir spill conditions. Internal reservoir processes associated with TDG are not as complicated as some other processes. W2 model version 3.1 was updated to support TDG modeling; as a result, the ability to use a common model capability to examine more than one parameter may have some advantages. A temperature model could also consider potential TDG model applications without major water quality data collection. However, if DO concentrations need to be modeled accurately, the complexity of the data sets and modeling increases exponentially.

Water quality parameters might include the interrelated DO, nutrient loading, and eutrophication processes, although obtaining sufficient data for this more involved reservoir application is more work and depends on the situation. Weakly stratified run-of-the-river reservoirs with high flow-through rates are typically easier to calibrate and require less data than strongly stratified, deep, long-term storage impoundments. Consequently, expanding the model to support oxygen series should be carefully planned according to each specific situation. Many W2 temperature models do not include DO and still provide much water quality management information. Spending years 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.

6.2 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-reservoir model development should be considered when collecting data.

6.2.1 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.

6.2.2 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 a thousand 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.

6.3 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 and incorporate density gradient adjustments. Analysis of other data sources, including new continuous thermistor data and vertical profile data, could help in confirming model data sets and 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 2D reservoir models; expansion to include other parameters would likely require additional review and discussion. The following actions include a staged approach for refining water quality data for reservoir modeling purposes.

(1) 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 reservoir modeling and is advantageous to help define the appropriate model approach and resources needed for model development.

(2) Collect physical parameters from surface-to-bottom profiles at selected sites in the reservoir that correlate with the inflow-outflow data and would supplement existing historical profile data. Profiles at the dam forebay for calibration and at the first deep inflow area for checking inflow to the main body of the reservoir are important. Specific Hydrolab, In-Situ, YSI, or similar water quality devices can measure temperature, pH, conductivity, and DO. Optional parameters might include TDG and oxidation-reduction

potential (ORP). Monthly profiles at three to four stations, including downstream of major inflow tributaries for each major arm of the reservoir, are suggested for the initial series. Additional profiles in the reservoir could be added at a future date, depending on the initial series and analysis of other data sources. Pump-storage operations may require further specialized evaluation.

(3) Conduct initial limited testing of the existing reservoir model for evaluating the ability to expand temperature modeling for year-round simulation, for examining adjustments to density gradients, and for assessing the need to update the model to version 3.5 (or a newer research version of the W2 model) and 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.

(4) Evaluate potential action alternatives associated with ongoing basin water use planning and evaluate reservoir modeling priorities, water quality parameters, and model support requirements. Cooperation is required between participants who have technical expertise in water quality modeling, reservoir limnology, fisheries, and project operations.

7.0 Meteorological Data

Meteorological data are an essential part of reservoir hydrodynamic models. These data provide the basis for coefficients applied in model equations affecting reservoir mixing and 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 reservoirs due to large fluctuations in wind. There are often numerous National Weather Service (NWS), agricultural, and other nearby meteorological stations. Three or more nearby stations surrounding the reservoir can often be used to provide average hourly meteorological data and fill in data gaps.

7.1 Meteorological Data for Reservoir Modeling

As a minimum, the following information is needed:

Meteorological data including: hourly drybulb (air) temperature (°C), dewpoint temperature (°C), windspeed (meters per second), wind direction (radians), solar radiation (kcal/m^2/hr), and cloud cover. Meteorological data should be determined from the nearest meteorological station recording at 2 meters above the ground. Wind speed collected at a different height can be adjusted in the W2 model. 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 useful.

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 near the dam or main pool of water. Parameters such as 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).

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

7.1.1 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 throughout the reservoir area. The stations might be installed through a cooperative effort and linked into a remote AgriMet monitoring network.

For long reservoirs, more than one meteorological station might need to be installed. Dominant wind patterns affecting internal seiching (sloshing) and water circulation may be important to water quality model calibration. Model calibration requires adequately representing the mixing and development of the warm, well-mixed surface layers.

7.1.2 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 2D reservoir modeling.

Parameters collected at new meteorological stations may include:

- 24 hourly air temperature - time step, mean, minimum, and maximum records

- 24 hourly precipitation - accumulated precipitation for water year
- Hourly wind speed and wind direction - average conditions for hour
- Hourly solar radiation - accumulated global (direct) solar radiation
- Mean hourly dew point temperatures
- Relative humidity - mean daily relative humidity
- Barometric pressure - time step, 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 reservoir and determining appropriate coefficients to include in reservoir modeling. New data will also provide an important reference for analyzing and adjusting historical meteorological data.

7.2 Meteorological Data Gaps and Model Considerations

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

1. Examine data produced by new meteorological stations often to ensure proper function of equipment and proper QA/QC.

2. At end of the first year, review meteorological data, begin setting up methods for data analysis, and begin conversion of new and historic data sets for use in the reservoir water quality model.

3. Compare newly collected data to nearby meteorological stations at similar elevation. Determine and document differences due to lake effects, vegetative cover, and topography.

4. Delete or note incorrect, negative, or unusually high or low outliers, depending on seasonal conditions.

5. Select similar meteorological stations and fill in data gaps in input data sets.

6. 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.

7. Site visit to visually see if sampling and meteorological stations appear to be in representative locations.

8.0 Data Collection Priorities and Practical Considerations

Discussions with those who have experience in previous reservoir limnology, monitoring, and modeling studies are helpful in gaining insight into technical issues. Practical experience is important to development of modeling capabilities for a reservoir. 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 reservoir model data collection.

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

8.1 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. Knowing 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 reservoir be conducted to view and talk with local dam operators and 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) 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 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 inflow, reservoir profile, and outflow locations. Hourly meteorology can often be found at a nearby site. Visiting the chosen meteorological site during a site visit often can be revealing. A calibrated temperature model, in combination with DO and conductivity profiles, can often answer many water quality related questions or can identify dominant mixing, interflow, and water quality issues. However, if low DO, eutrophication, internal recycling of nutrients, anaerobic sediments, 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 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 going to the 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.

8.2 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 at 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 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.

8.3 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. Model calibration requires an entire set of many 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 W2 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.

8.4 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 meta data. Processing of data should be optimized by common standardized software, statistical techniques, and averaging, rather than meticulous manual input and manipulation where possible.

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.

9.0 Conclusions

A calibrated reservoir model can be a useful tool for managing the water quality of a natural resource. The resulting modeling capabilities are customized to specific characteristics of the 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 conditions in the reservoir 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

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, 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.

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.

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.

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.

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, Thomas M., 1994. “CE-QUAL-W2, Version 2.0,” Vol. E-94-1.

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

USACE, 1995. CE-QUAL-W2: "A Two-Dimensional, Laterally-Averaged, Hydrodynamic and Water Quality Model, Version 2.0 - User Manual." Instruction Report EL-95-1, Prepared by T.M. Cole and E.M. Buchak for the U.S. Army Corps of Engineers, 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*. Third Edition. Academic Press, New York, New York..