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ABSTRACT: CE-QUAL-W2 is a two-dimensional (longitudinal-vertical) water quality and hydrodynamic computer simulation model that was originally developed for deep, long, and narrow waterbodies. The current model, Version 2, has been used in over 200 river, reservoir/lake, and estuary applications throughout the U.S. and abroad. Version 2, though, cannot accommodate systems that have a significant sloping water surface since the vertical coordinate system is aligned with gravity and vertical accelerations are neglected. The governing equations for CE-QUAL-W2 were re-derived so that it could be applied to entire river basins including river-estuary, lake-river, and reservoir-river systems with channel slopes. This re-derivation is one of many improvements for the Version 3 code. Other improvements include improved numerical schemes, improved and additional water quality algorithms, and algorithms for addition of hydraulic structures (weirs, gates, culverts) between model segments. Test cases for this new code include a 244 km section of the Lower Snake River in Idaho and Oregon; the Bull Run River basin composed of 3 water supply reservoirs and 2 river sections with a 2.2% and a 1.4% average slope in the Oregon Cascade mountains; and the Columbia Slough system in Portland, OR, composed of 33 separate lake systems connected by hydraulic structures and a fresh-water tidal region.

1 INTRODUCTION

CE-QUAL-W2 is a two-dimensional water quality and hydrodynamic code supported by the USACE Waterways Experiments Station (Cole and Buchak, 1995). This model has been widely applied to stratified surface water systems such as lakes, reservoirs, and estuaries and computes water levels, horizontal and vertical velocities, temperature, and 21 other water quality parameters (such as dissolved oxygen, nutrients, organic matter, algae, pH, the carbonate cycle, bacteria, dissolved solids, and suspended solids).

This paper documents the development of CE-QUAL-W2 Version 3 incorporating sloping riverine sections. Version 3 has the capability of modeling entire watersheds with rivers and inter-connected lakes, reservoirs, or estuaries. Three example applications are shown illustrating the use of Version 3.

2 RATIONALE FOR DEVELOPMENT OF RIVER BASIN MODEL FOR CE-QUAL-W2

CE-QUAL-W2 has been in use for the last two decades as a tool for water quality managers to assess the impacts of management strategies on reservoirs, lakes, and estuaries. A predominant feature of the model is its ability to compute the two-dimensional velocity field for narrow systems that stratify. In contrast to many reservoir models that are zero-dimensional hydrodynamic models, the ability to simulate transport accurately can be as important as the water column kinetics in simulating water quality accurately.

One limitation of CE-QUAL-W2 Version 2 is its inability to model sloping riverine waterbodies. Models, such as WQRSS (Smith, 1978), HEC-5Q (Corps of Engineers, 1986), and HSPF (Donigian et al., 1984), have been developed for water basin modeling but have serious limitations. The HEC-5Q (similar to WQRSS) and HSPF models incorporate a one-dimensional longitudinal river model with a one-dimensional vertical reservoir model (only one-dimensional in temperature and water quality and zero dimensional in hydrodynamics). The modeler must choose the location of the transition from 1-D longitudinal to 1-D vertical. Besides the limitation of not solving for the velocity field in the stratified, reservoir system, any point source inputs to the reservoir section are spread over the entire longitudinal distribution of the reservoir layer.

Other hydraulic and water quality models in common use for unsteady flow include the 1-D dynamic EPA model DYNHYD (Ambrose, et al., 1988), used together with the multidimensional water quality model WASP. WASP relies on DYNHYD for 1-D hydrodynamic predictions. If WASP is used in a multidimensional schematization, the modeler must specify dispersion coefficients to allow transport in the vertical and/or lateral directions or use another hydrodynamic model that explicitly includes these effects. Also, the Corps model, CE-QUAL-RIV1 (Environmental Laboratory, 1995), is a one-dimensional dynamic flow and water quality model used for one-dimensional river or stream sections. None of these models have the ability to characterize adequately the hydraulics or water quality of deeper reservoir systems or deep river pools that stratify.

In the development of CE-QUAL-W2 Version 2, vertical accelerations were considered negligible compared to gravity forces. This assumption lead to the hydrostatic pressure approximation for the z-momentum equation. In sloping channels, this assumption is not always valid because vertical accelerations cannot be neglected if the z-axis is aligned with gravity. Also, the current Version 2 algorithm does not allow the upstream bed elevation to be above the downstream water surface elevation. Because water basin modeling is becoming more important for water quality managers, providing the capability for CE-QUAL-W2 to be used as a complete tool for water basin modeling is an essential step in improving the current state-of-the-art.

3 VERSION 3 RIVER BASIN MODEL

The river basin model was developed by re-deriving the governing equations assuming that the 2-D grid is adjusted by the channel slope such that each waterbody in the system is represented by a channel slope (Figure 1).

Having 2-D river sections has advantages in modeling the following processes: sediment deposition and scour, particulate (algae, detritus, suspended solids) sedimentation, and sediment flux processes. Also the channel friction factor can be stage invariant (see Wells, 1999) using a 2-D hydrodynamic model compared to a 1-D model.

Details of deriving the governing equations for CE-QUAL-W2 Version 3 for the river basin model are shown in Wells (1997). Table 1 shows the governing equations after lateral averaging for an arbitrary channel slope.

Numerous algorithmic changes were made in the CE-QUAL-W2 model. In addition to the general channel sloping feature, these changes included:

- The model user can choose
    - ❑ turbulence closure models for each waterbody using eddy-viscosity mixing length models
    - ❑ varying vertical grids between waterbodies
    - ❑ Chezy or Manning's friction factors
    - ❑ reaeration formulae based on the riverine or reservoir/lake or estuary character of the waterbody or user-defined formulations
    - ❑ evaporation models based on theory or user-defined formulations
- A branch could be linked linearly with another branch or could have an internal dam or internal hydraulic structure(s) (spillways, gates, weirs, and pipes) within or between water bodies (The pipes

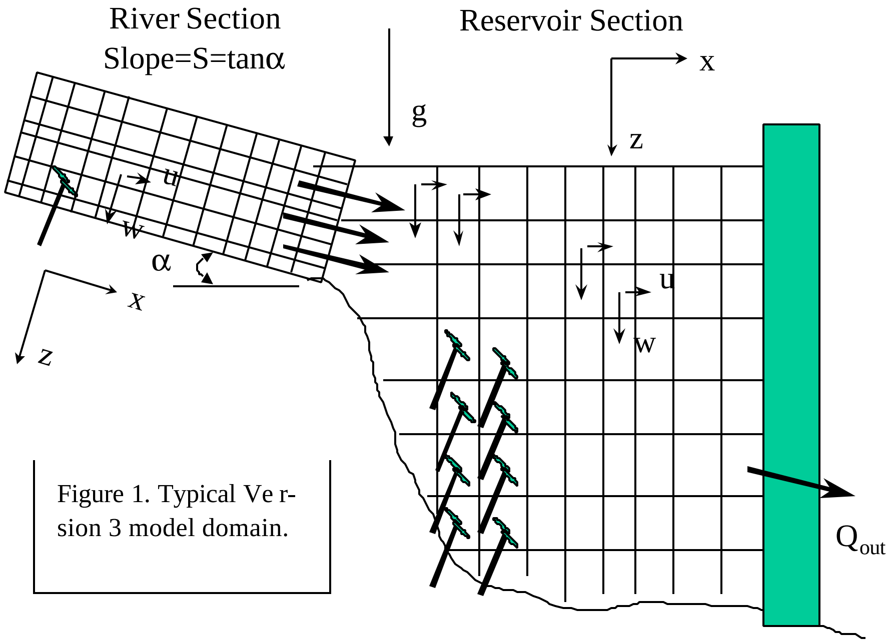

Figure 1. Typical Version 3 model domain.

Table 1. Governing equations for CE-QUAL-W2 Version 3.

Equation	Version 3 governing equations
x- momentum	$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+\frac{\partial WUB}{\partial z}= gB\sin\alpha+g\cos\alpha B\frac{\partial\eta}{\partial x}-\frac{g\cos\alpha B}{\rho}\int_{\eta}^{z}\frac{\partial\rho}{\partial x}dz+\frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x}+\frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z}+qBU_x$
z-momentum	$0=g\cos\alpha-\frac{1}{\rho}\frac{\partial P}{\partial z}$
free surface equation	$B_\eta\frac{\partial\eta}{\partial t}=\frac{\partial}{\partial x}\int_{\eta}^{h}UBdz-\int_{\eta}^{h}qBdz$
Equation of state	$\rho = f(T_w,\Phi_{TDS},\Phi_{ss})$
Conservation of mass/heat	$\frac{\partial B\Phi}{\partial t}+\frac{\partial UB\Phi}{\partial x}+\frac{\partial WB\Phi}{\partial z}-\frac{\partial\left(BD_x\frac{\partial\Phi}{\partial x}\right)}{\partial x}-\frac{\partial\left(BD_z\frac{\partial\Phi}{\partial z}\right)}{\partial z}=q_\Phi B+S_\Phi B$

Note: U,W: horizontal and vertical velocity, B: channel width, P: pressure, g: acceleration due to gravity, τ_x,τ_z: lateral average shear stress in x and z, ρ: density, η: water surface, α: channel angle, U_x: x-component of velocity from side branch, q: lateral inflow per unit length, $f(T_w,\Phi_{TDS},\Phi_{ss})$: density function dependent upon temperature, total dissolved solids or salinity, and suspended solids; Φ: laterally averaged constituent concentration, D_x: longitudinal temperature and constituent dispersion coefficient, D_z: vertical temperature and constituent dispersion coefficient, q_Φ: lateral inflow or outflow mass flow rate of constituent per unit volume, S_Φ: laterally averaged source/sink term.

algorithm is an unsteady 1-D hydrodynamic sub-model to the core W2 code from Berger and Wells, 1999.)

- The effect of hydraulic structures on gas transfer and total dissolved gas transport was formalized into the code
- At intersections between main branches and side branches, conservation of longitudinal momentum was preserved
- The effect of lateral inflows from tributaries or the lateral component of inflows from branch intersections on the vertical eddy viscosity was included

Additional Version 3 code changes include updated numerical schemes (Ultimate-Quickest), an implicit vertical eddy viscosity formulation, multiple suspended inorganic particle sizes, multiple algal types and carbon species, and a sediment diagenesis model.

4 APPLICATION TO THE LOWER SNAKE RIVER, USA

The domain of the Lower Snake River from C. J. Strike Reservoir (RM 487) to the headwaters of Brownlee Reservoir (RM 335) was 244 km (152 miles) in length. The river was broken into 5 branches of varying slope from 0.001 to 0.0008. The model consisted of 312 longitudinal segments between 805 and 835 m in length, 13 tributary and point sources, 1 distributed load, and 90 agricultural return flows.

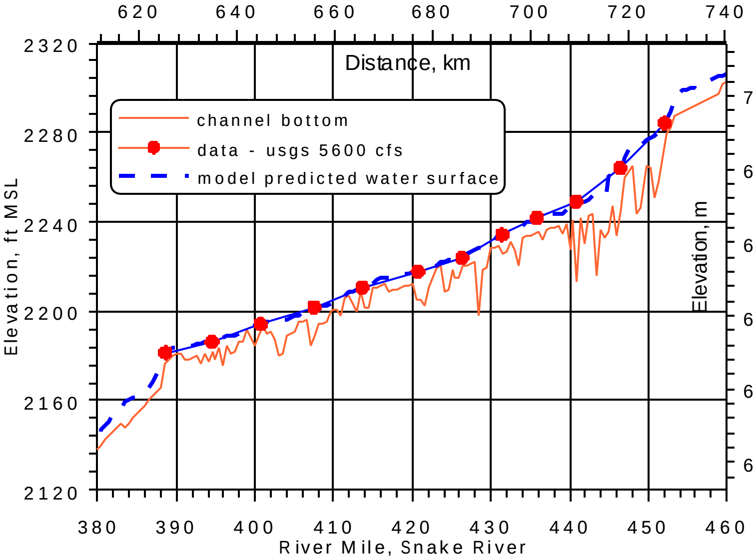

Figure 2. Comparison of water surface model predictions and data at 5600 cfs.

Model hydraulics were calibrated using water surface elevation data at specific flow rates. Gaging station data were available at several locations throughout the domain. Figure 2 shows the water level calibration for a flow of 5600 cfs. Mean water level error and root mean square water level error for flow rates between 5600 cfs and 13000 cfs were well below 0.5 ft for a river that experiences a 300 ft drop over its length. The calibrated Chezy values varied from segment to segment between 20 and 80 and were flow and stage invariant.

The primary goal of this modeling study was to determine the loading of organic matter and nutrients to Brownlee Reservoir. Model predictions of temperature, algae, nutrients and organic matter compared well with field data at 6 locations along the river.

5 APPLICATION TO THE BULL RUN RIVER SYSTEM, USA

The Bull Run watershed has been the primary drinking water supply since 1895 for the metropolitan area of Portland, OR, USA. The watershed is composed of 2 man-made reservoirs (Reservoir 1 and 2), and a potential 3rd reservoir. Because of compliance requirements for endangered species survival, the reservoirs and river segments in the watershed were

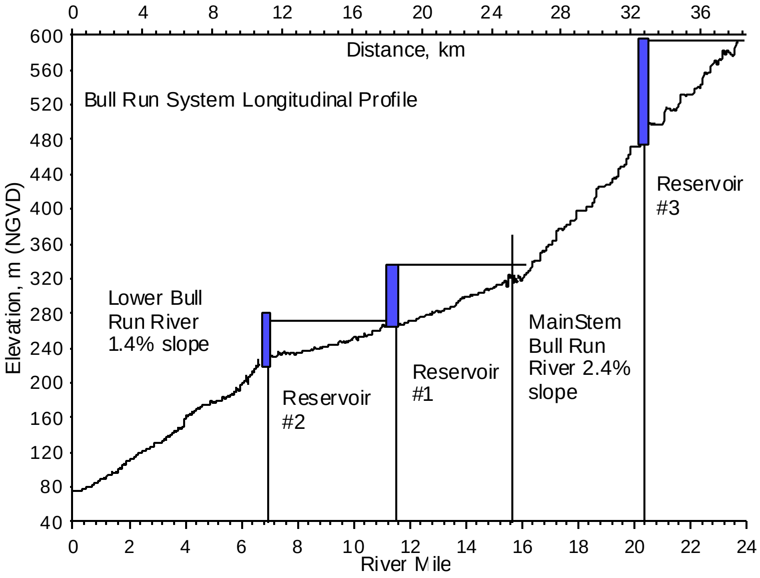

Figure 3. Bull Run River-Reservoir system profile.

modeled with Version 3 in order to meet temperature standards for fish. Figure 3 shows the profile of the model system including 2 river and 3 reservoir sections.

Model predictions of temperature profiles in the two reservoirs during a two-year continuous simulation period were within 0.5°C Absolute Mean Error and 0.6°C Root Mean Square error for over 40 profile comparisons in each reservoir. A typical series of model-data predictions for Reservoir 1 are shown in Figure 4.

A dye study performed in the Lower Bull Run River during June 1999 was used as a basis to verify the river model travel times and dispersive characteristics. Model-data comparisons are shown in Figure 5 using the Quickest-Ultimate numerical scheme.

6 APPLICATION TO THE COLUMBIA SLOUGH SYSTEM, USA

The Columbia Slough is an extensive system of interconnected wetlands, channels, and lakes located in the Portland, Oregon, USA metropolitan area and lying in

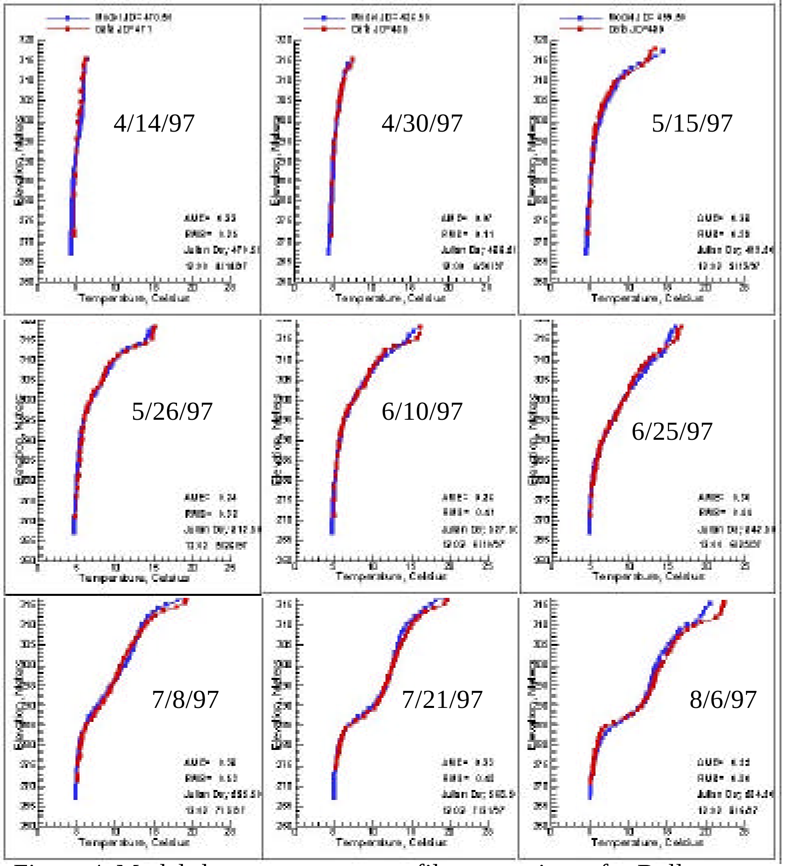

Figure 4. Model-data temperature profile comparisons for Bull Run Reservoir 1 during 1997.

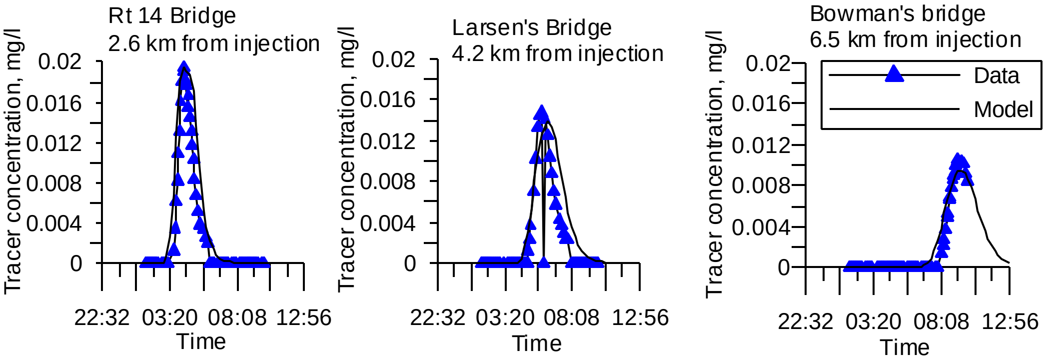

Figure 5. Comparison of computed versus observed dye concentrations in the Lower Bull Run River June 1999.

the floodplain of the Columbia River. It is approximately 30 km in length and includes a fresh-water estuary portion and a series of isolated lakes and channels that receive stormwater and groundwater inflows.

The model was developed to evaluate the effect of combined sewer overflows, stormwater, and groundwater inflows on water quality in the Columbia Slough system. The model development is summarized in Berger and Wells (1999).

The model's ability to capture velocities in the tidally dominated Lower Slough is shown in Figure 6 during high-water conditions. CE-QUAL-W2 velocity predictions are laterally averaged whereas velocity measurements were taken at the channel center.

A test was also made of the Version 3 culvert algorithm. The Upper Columbia Slough is not tidally influenced but is a series of lakes and channels separated by culverts. Cyclic pumping at the westernmost end of the Upper Slough removes groundwater and stormwater inflows. A comparison of measured culvert flows using a continuous flow meter and the model predictions are shown in Figure 7.

The W2 model was also able to capture water hammer effects in the Upper Slough when the westernmost pump station changed pumping rates. A field test was performed where Upper Slough pumps were turned off to allow groundwater to raise water levels. The pumps were then turned on at their maximum pump capacity of 400 cfs and then throttled down to 175 cfs and 120 cfs until they were turned off.

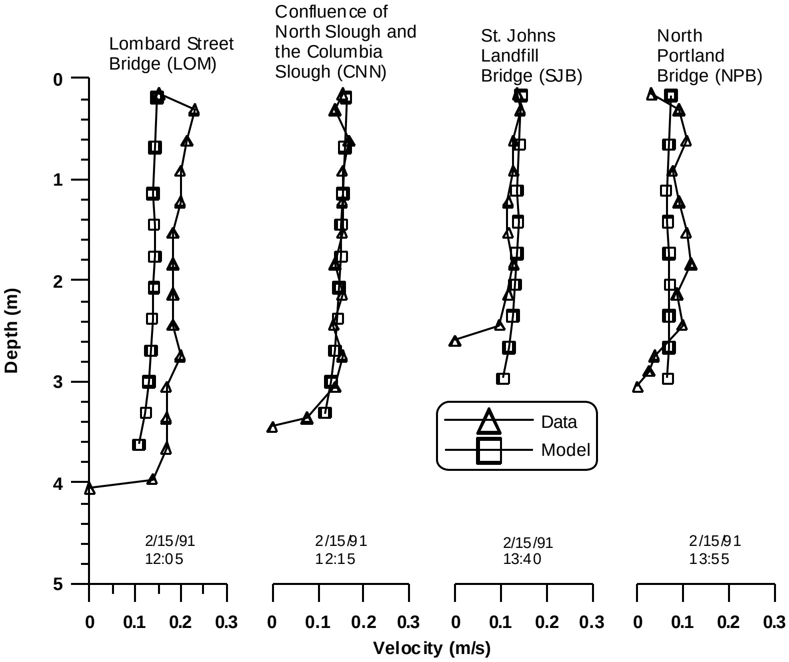

Figure 6. Measured centerline velocity compared to laterally averaged model predictions.

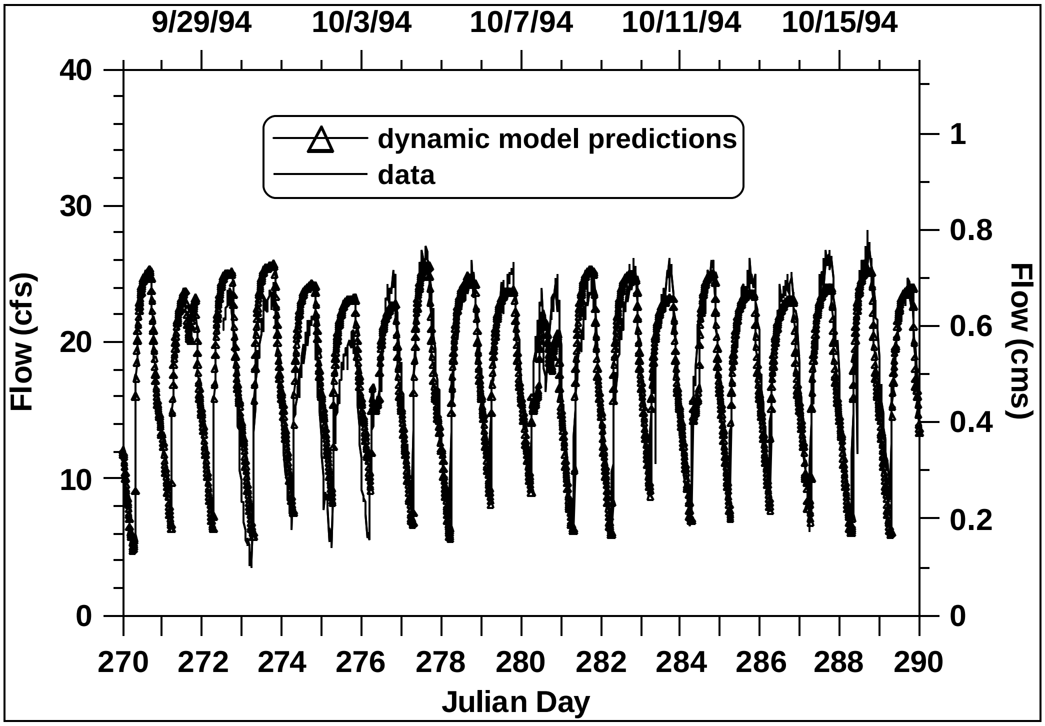

Figure 7. Model predictions of flow through culvert at NE47th in the Upper Slough compared to Flow tote measurements. This corrugated metal culvert is 69-ft long and 36-inch diameter.

Figure 8 shows a comparison of model predicted water levels and field data.

7 SUMMARY

A 2-D hydrodynamic and water quality model, CE-QUAL-W2 Version 3, was developed for river basin modeling that now allows the integration of river, reservoir/lake, and estuary systems. Three test cases were shown demonstrating the ability of the model to reproduce river and tidal hydraulics and temperature dynamics in stratified reservoirs. Further improvements in Version 3 are being explored including the application of a k-ε turbulence model rather than the existing mixing length model for the vertical transfer of momentum. Using a 2-D approach for river channels, in contrast to 1-D riverine models, allows the use of friction factors which are stage and flow invariant.

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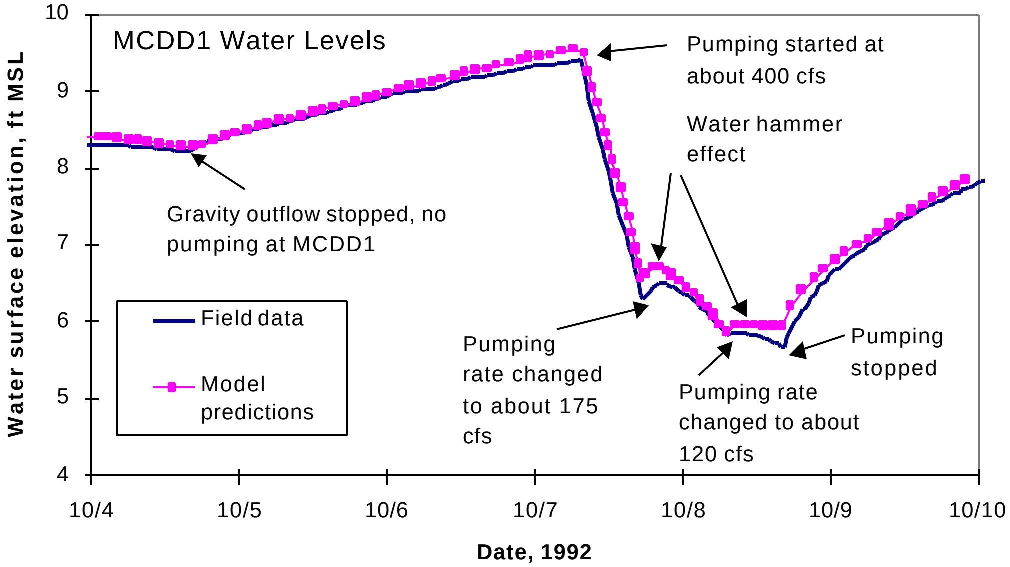

Figure 8. Water level predictions at MCDD1 during water level test compared to field data.

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