Hydrodynamic and water quality river basin modeling using CE-QUAL-W2 version 3

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Abstract

The 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, ability of the user to add hydraulic structures between model segments and the ability to model the effect of hydraulic structures on gas transfer. Test cases for this new code include a 244 km section of the Lower Snake River in the Northwestern USA; 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, USA; and the Columbia Slough system in Portland, OR, USA 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 [1]). 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). A typical grid for this model is shown in Figure 1 where the vertical axis is aligned with gravity.

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.

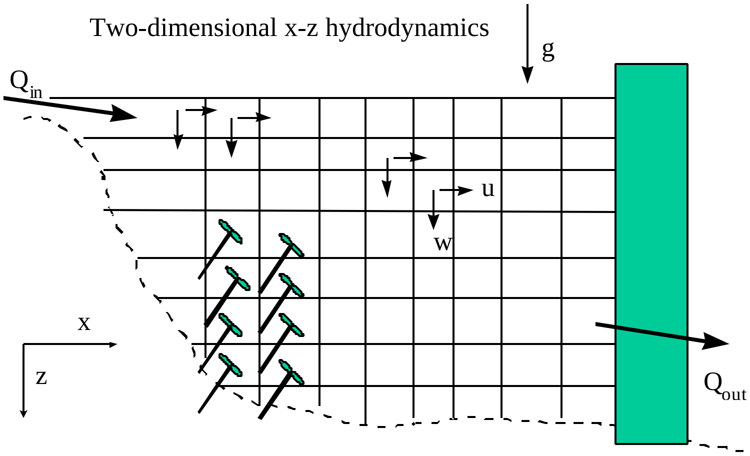

Figure 1. Typical CE-QUAL-W2 Version 2 model grid.

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 [2]), HEC-5Q (Corps of Engineers [3]), and HSPF (Donnigen et al. [4]), 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. [5]), used together with the multidimensional water quality model WASP. WASP relies on DYNHYD for 1-D hydrodynamic predictions. If WASP is used in a multi-dimensional 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 [6]), 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 Approach to the Problem

There were many approaches that could have been implemented to incorporate riverine branches within CE-QUAL-W2. By choosing a theoretical basis for the riverine branches that uses the existing CE-QUAL-W2 2-D computational scheme for hydraulics and water quality, the following benefits accrued:

- code updates in the computational scheme affected the entire model rather than just one of the computational schemes for either the riverine or the reservoir sections leading to easier code maintenance
- no changes were made to the temperature or water quality solution algorithms
- by using the two-dimensional framework, the riverine branches had the ability to predict the velocity and water quality field in two dimensions. This 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 [7]).

- since the entire watershed model had the same theoretical basis, setting up branches and interfacing branches involved the same process whether for reservoir or riverine sections, thus making code maintenance and model set-up easier.

The theoretical approach was to re-derive the governing equations assuming that the 2-D grid is adjusted by the channel slope (Figure 2).

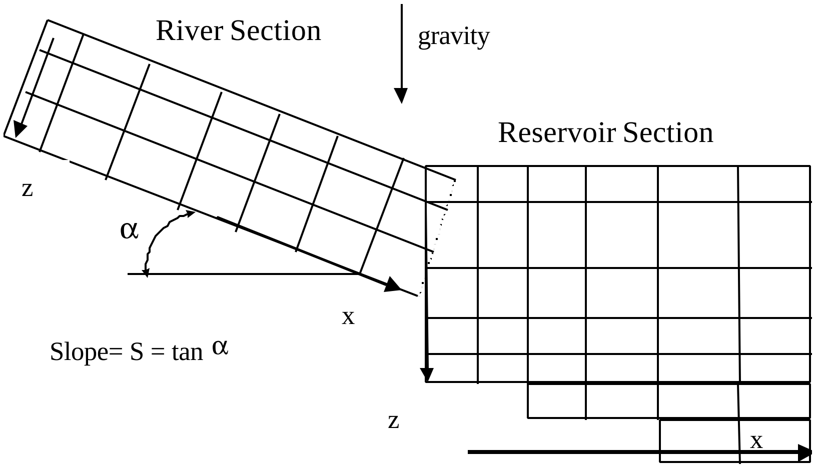

Figure 2. Conceptual schematic of river-reservoir connection.

4 River Basin Model

Details of deriving the governing equations for CE-QUAL-W2 Version 3 for the river basin model are shown in Wells [8]. Table 1 shows the governing equations after lateral averaging for a channel slope of zero (original model formulation) and for an arbitrary channel slope.

Equations unchanged from Version 2 model include the equation of state,

$$r = f(T_w, \Phi_{TDS}, \Phi_{ss})$$

where $f(T_w, \Phi_{TDS}, \Phi_{ss})$: density function dependent upon temperature, total dissolved solids or salinity, and suspended solids, and the conservation of mass (and heat) equation,

$$\frac{\partial B\Phi}{\partial t} + \frac{\partial UB\Phi}{\partial x} + \frac{\partial WB\Phi}{\partial z} - \frac{\partial\left(BD_x \frac{\partial \Phi}{\partial x}\right)}{\partial x} - \frac{\partial\left(BD_z \frac{\partial \Phi}{\partial z}\right)}{\partial z} = q_\Phi B + S_\Phi B$$

Table 1. Comparison of governing equations for CE-QUAL-W2 with and without channel slope.

Equation	Version 2 governing equations assuming no channel slope	Version 3 governing equations assuming an arbitrary channel slope and conservation of longitudinal momentum between branches
x-momentum	$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+$ $\frac{\partial WUB}{\partial z}=$ $gB\frac{\partial \eta}{\partial x}-\frac{gB}{\rho}\int_{\eta}^{z}\frac{\partial \rho}{\partial x}dz+$ $\frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x}+\frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z}$	$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+\frac{\partial WUB}{\partial z}=$ $gB\sin\alpha+g\cos\alpha B\frac{\partial \eta}{\partial x}-$ $\frac{g\cos\alpha B}{\rho}\int_{\eta}^{z}\frac{\partial \rho}{\partial x}dz+$ $\frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x}+\frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z}+qBU_x$
z-momentum	$0=g-\frac{1}{\rho}\frac{\partial P}{\partial z}$	$0=g\cos\alpha-\frac{1}{\rho}\frac{\partial P}{\partial z}$
free surface equation	$B_{\eta}\frac{\partial \eta}{\partial t}=\frac{\partial}{\partial x}\int_{\eta}^{h}UBdz-\int_{\eta}^{h}qBdz$	$B_{\eta}\frac{\partial \eta}{\partial t}=\frac{\partial}{\partial x}\int_{\eta}^{h}UBdz-\int_{\eta}^{h}qBdz$

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

where 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.

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 could choose
    - ☐ turbulence closure models for each waterbody using eddy-viscosity mixing length models
    - ☐ varying vertical grids between waterbodies
    - ☐ Chezy or Manning's friction factor
    - ☐ 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 algorithm is an unsteady 1-D hydrodynamic sub-model to the core W2 code from Berger and Wells [9].)
- 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 algal types and carbon species, and a sediment diagenesis model.

5 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.

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 10 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.

6 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 modeled with Version 3 in order to meet

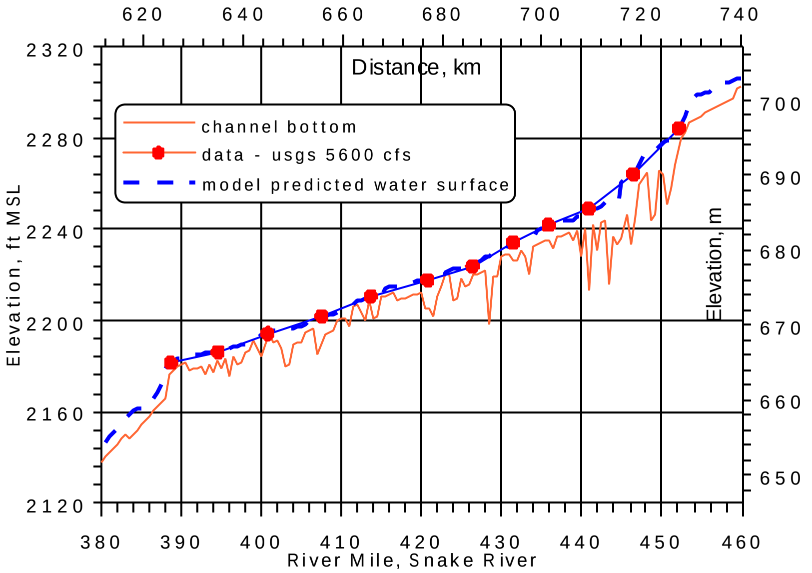

Figure 3. Comparison of model predictions and data of water surface along a portion of the Lower Snake River at a flow of 5600 cfs.

temperature standards for fish. Figure 4 shows the profile of the model system including 2 river and 3 reservoir sections. River channel slope was, on average, greater than 2% in the Upper Bull Run River.

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 5.

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 6 using the Quickest-Ultimate numerical scheme.

7 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 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

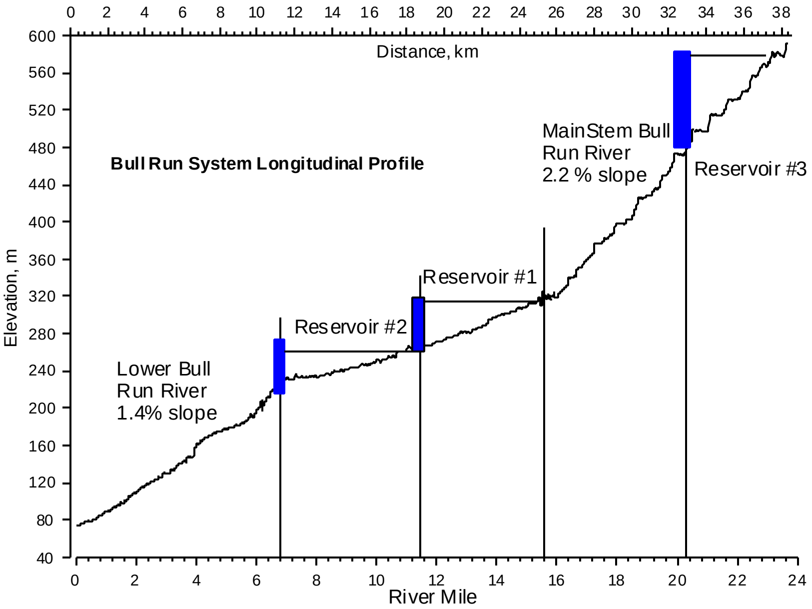

Figure 4. Bull Run River-Reservoir system profile.

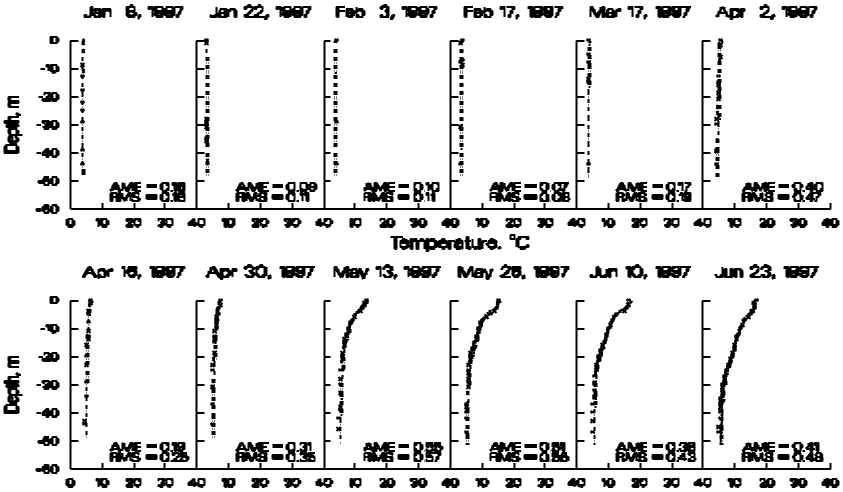

Figure 5. Model-data temperature profile comparisons for Reservoir 1 during 1997.

system. The model development is summarized in Berger and Wells [9].

The model's ability to capture velocities in the tidally dominated Lower Slough is shown in Figure 7 during high-water conditions. CE-QUAL-W2 velocity

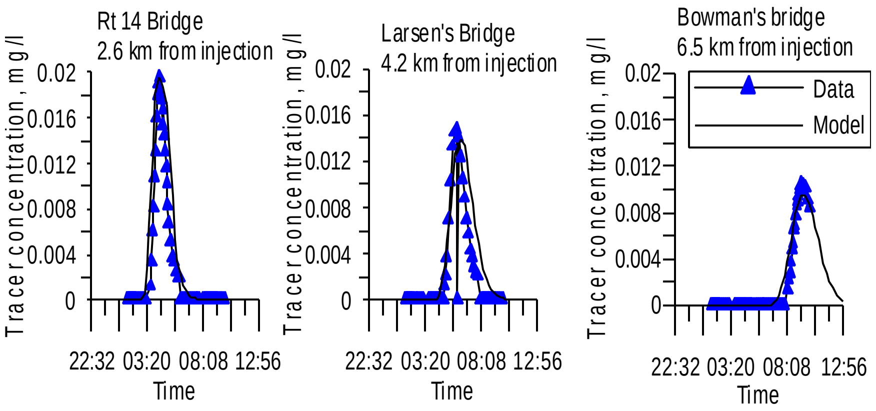

Figure 6. A comparison of computed versus observed dye concentrations in the Lower Bull Run River during June 1999.

predictions are laterally averaged whereas velocity measurements were taken at the channel center.

8 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.

9 Acknowledgments

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10 References

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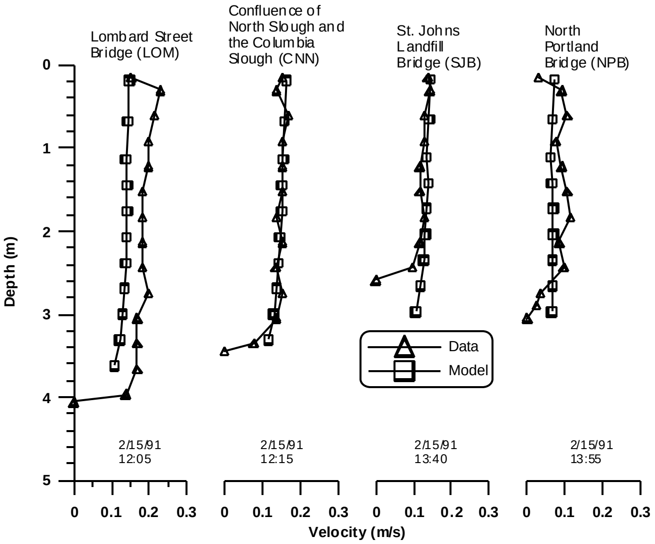

Figure 7. Measured centerline vertical velocity profiles compared to laterally averaged model predictions during high-water conditions.

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