Proceedings ASCE International Water Resources Engineering Conference
August 8-12, 1999, Seattle, WA

River Basin Modeling Using CE-QUAL-W2 Version 3

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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. A typical grid for this model is shown in Figure 1 where the vertical axis is aligned with gravity.

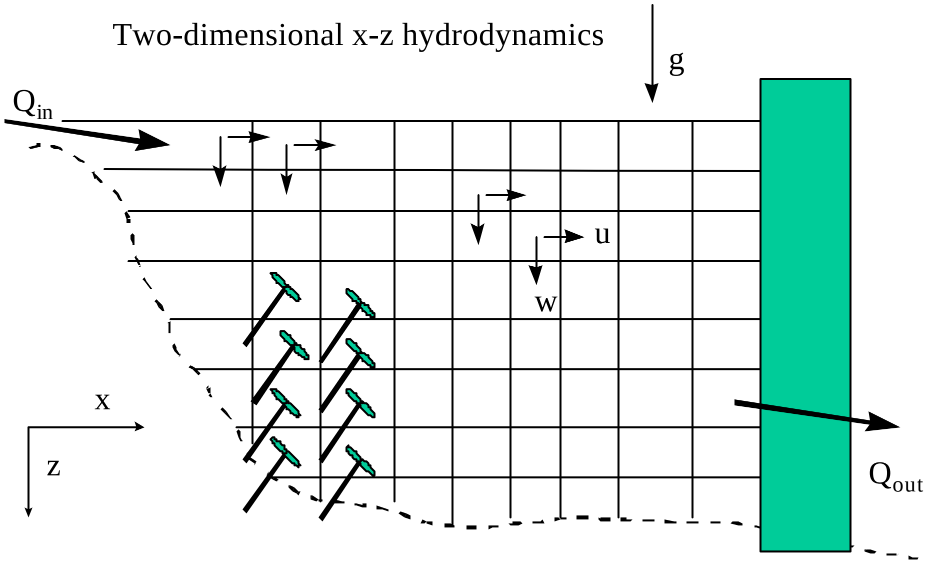

Figure 1. Typical grid for CE-QUAL-W2 Version 2.

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.

This task was accomplished by re-deriving the governing equations for a general channel slope. Many algorithmic model changes were made in concert with the re-derivation of the governing equations so that river basin simulations could be performed.

Rationale for Development of River Basin Model for CE-QUAL-W2

CE-QUAL-W2 has been in use for the last couple of decades as a tool for water quality managers to assess the impacts of management strategies on reservoir, lake, and estuary systems. 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

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hydrodynamic models, an understanding of the fluid mechanical transport can be as important as the reaction kinetics in the water column in predicting water quality changes.

One limitation of CE-QUAL-W2 Version 2 is its inability to model sloping river stretches. Models, such as WQRSS (Smith, 1978), HEC-5Q, and HSPF (Donnigen et al., 1984), have been developed for water basin modeling but have serious limitations. One issue is that 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 cell.

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 multi-dimensional schematization, the modeler must supply dispersion coefficients to allow transport in the vertical or lateral directions. 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. Each of these models do not have the ability to characterize adequately the hydraulics or water quality of deeper reservoir systems or deep river pools that stratify.

CE-QUAL-W2 Version 2, even though able to handle narrow systems that stratify, is not well-suited for one-dimensional river channels. In the development of CE-QUAL-W2, vertical accelerations were considered negligible compared to gravity forces. This assumption lead to the approximation of hydrostatic pressure for the z-momentum equation. In sloping channels, this assumption is not always valid because the vertical accelerations cannot be neglected if the x and z axes are aligned with an elevation datum and gravity, respectively. Also, the current CE-QUAL-W2 algorithm does not allow the upstream bed elevation to be above the downstream water surface elevation. Because water basin modeling is becoming more and more essential 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 upgrading the current state-of-the-art in modeling river basins.

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.
- 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. This is shown schematically in Figure 2.

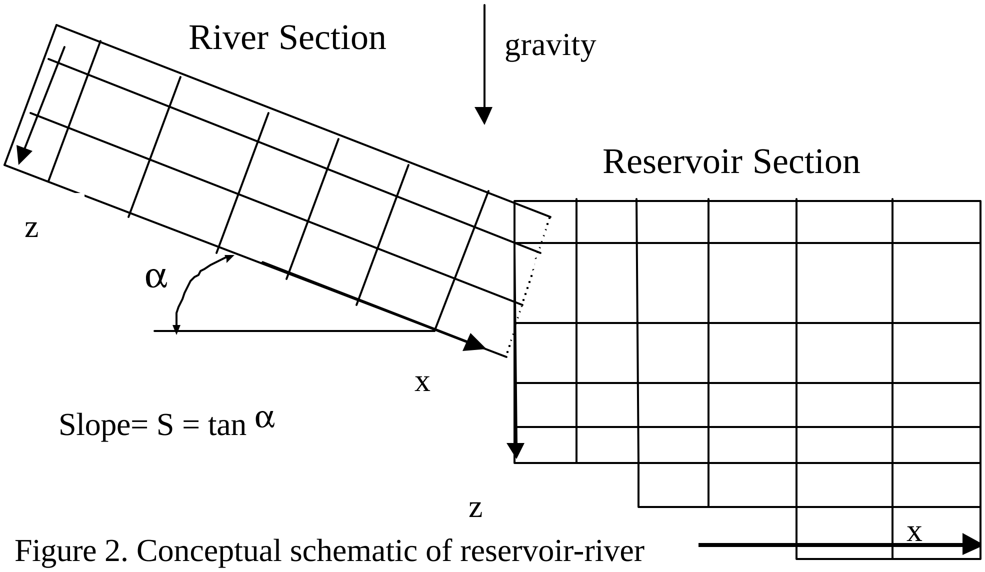

Figure 2. Conceptual schematic of reservoir-river connection.

The turbulence closure hypothesis used in reservoir sections was not adequate for the riverine sections. Hence, various turbulence closure hypotheses were updated for use in the model riverine sections.

River Basin 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 a channel slope of zero (original model formulation) and for an arbitrary channel slope. Parameters used in Table 1 are illustrated in Figure 3.

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

- The model user could choose
    - ❑ turbulence closure 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

- A branch could be linked linearly with another branch or could have an internal dam or internal hydraulic structures (spillways, gates, weirs) within or between water bodies
- At intersections between main branches and side branches, conservation of longitudinal momentum was maintained
- Tributaries and inflows now could affect the vertical mixing in a stratified receiving water by accounting for cross-shear momentum's effect on vertical mixing.

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

Equation	Existing governing equation assuming no channel slope	Governing equation 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

CE-QUAL-W2 coordinate system: $\alpha>0$

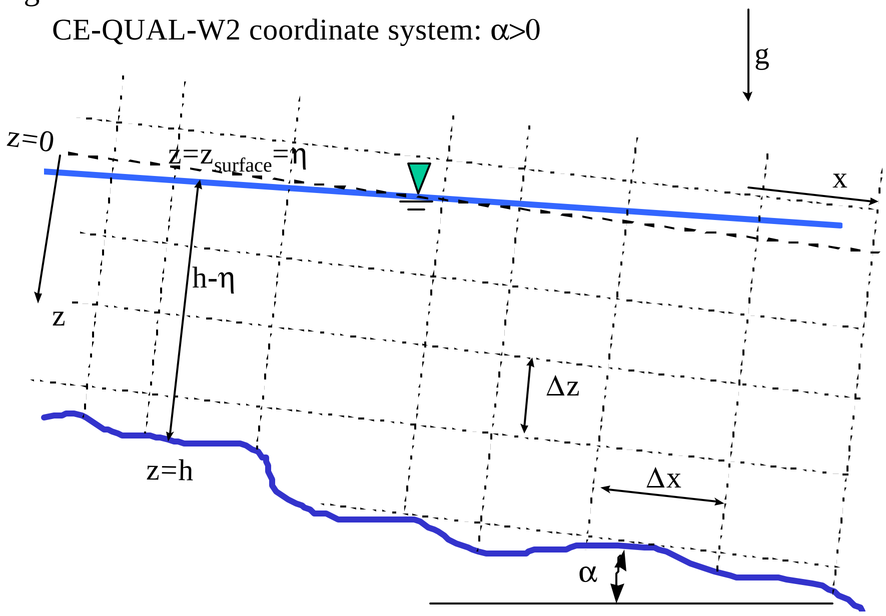

Figure 3. W2 coordinate system with finite channel slope.

Effect of 2-D Vertical Velocity Profile on Model Hydraulic Predictions

In contrast to other riverine models that assume vertically well-mixed systems, the Version 3 model accounts for the vertical variation of velocity in a riverine reach. Even though there is an added computational burden of computing the 2-D velocity profile, the advantage of making this computation is that the friction factor (Manning's or Chezy) for a segment can be flow or stage invariant.

Many one-dimensional hydraulic flow models, such as CE-QUAL-RIV1 and UNET (Barkau, 1997), allow the model user to specify how Manning’s friction factor changes with depth. The Mannning’s friction factor has been thought to vary as a function of depth, Reynolds number, roughness factor (or scale of bed grain size) (Ugarte and Madrid, 1994; Soong, DePue, and Anderson, 1995). Some of these formulations for variation of Manning's friction factor with hydraulic radius are shown in Figure 4.

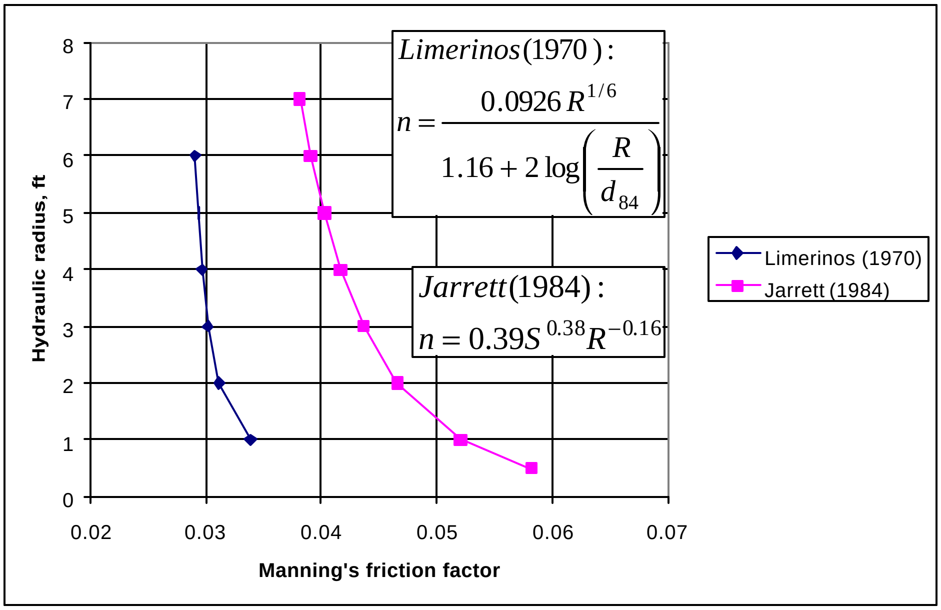

Figure 4. Variation of Manning's friction factor using formulae from Limerinos (1970) and Jarrett (1984) for S=0.0005 and d_{84}=50

Researchers understand that the friction factor, when representing a hydraulic element with uniform roughness, should be flow invariant with depth (Henderson 1966). But many assert that the friction factor changes with depth because the friction coefficient is variable with the wetted perimeter. Some reason that it is to be expected that at shallow depths the larger size of the bed material produces a higher overall friction factor than a deeper flow where the side walls may have a smaller friction.

Since most researchers used 1-D cross-sectionally averaged flow equations (such as Manning’s Equation, or 1-D dynamic hydraulic models), this parameterization itself has been responsible for the seeming variation of Manning’s friction factor with depth. For example, all one-dimensional hydraulic models implicitly assume that the rate of transfer of momentum from the bottom of the channel to the top is infinite. For these hydraulic models, even as the depth of the channel increases, these models still assume an infinite rate of transfer of momentum from the channel bottom to the surface. Hence, as the water depth increases, the apparent friction factor must be reduced because of the assumption of infinite momentum transfer between the bed and the water surface.

But, in a 2-D (vertical-longitudinal) river model, the Manning's friction factor does not have to be varied with stage in order to produce the effect that as the river stage increases, the apparent friction decreases. The water surface set-up for various number of layers changes significantly as the layer numbers increase. In general, the water surface slope increases as the number of layers decreases. In other words, the average eddy viscosity in the water column increases as the number of layers decrease until at the limit of a one-layer system, the average vertical eddy viscosity is infinite. The fact that the Manning’s friction factor seems to decrease with depth in 1-D models is accounted for in modeling the river channel as a 2-D (vertical-longitudinal) system.

CE-QUAL-W2 Version 3 uses five different vertical eddy viscosity formulations. These formulations are shown below in Table 2.

Table 2. Vertical eddy viscosity, ν_t, formulations used with the Version 3 model.

Formulation	Formula (definitions of variables are shown below)	Reference
Nickuradse (NICK)	$\nu_t = \ell_m^2 \left\vert\frac{\partial u}{\partial z}\right\vert e^{-CRi}$ $\ell_m = H\left[0.14 - 0.08\left(1-\frac{z}{H}\right)^2 - 0.06\left(1-\frac{z}{H}\right)^4\right]$	Rodi (1993)
Parabolic (PARAB)	$\nu_t = \kappa u_* z\left(1-\frac{z}{H}\right)e^{-CRi}$	Engelund (1976)
W2	$\nu_t = \kappa\left(\frac{l_m^2}{2}\right)\sqrt{\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\tau_{wy} e^{-2kz}}{\rho \nu_t}\right)^2}\ e^{(-CRi)}$ $\ell_m = \Delta z_{max}$	Cole and Buchak (1995)
W2 with mixing length of Nickuradse (W2N)	$\nu_t = \kappa\left(\frac{l_m^2}{2}\right)\sqrt{\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\tau_{wy} e^{-2kz}}{\rho \nu_t}\right)^2}\ e^{(-CRi)}$ $\ell_m = H\left[0.14 - 0.08\left(1-\frac{z}{H}\right)^2 - 0.06\left(1-\frac{z}{H}\right)^4\right]$	Cole and Buchak (1995) and Rodi (1993)
RNG (re-normalization group)	$\nu_t = \nu\left[1+\Psi\left(3\kappa\left(\frac{zu_*}{\nu}\right)^3\left(1-\frac{z}{H}\right)^3 - C_1\right)\right]^{1/3} e^{-CRi}$	Simoes (1998)
where ℓ_m: mixing length, z: vertical coordiante, H: depth, u: horizontal velocity, Ri: Richardson number, C: constant (assumed 0.15), u_*: shear velocity, κ von Karman constant, τ_{wy}: cross-shear from wind, k: wave number, ρ: liquid density, Δz_{max}: maximum vertical grid spacing, $\Psi(x)=\max(0,x)$, ν: molecular viscosity, C_1: empirical constant (assumed 100)		

Typical variation of these formulations, as predicted with the CE-QUAL-W2 model, is shown in Figure 5 for Manning's fiction factor for an open-channel, non-stratified flow regime as compared to theory of steady uniform channel flow.

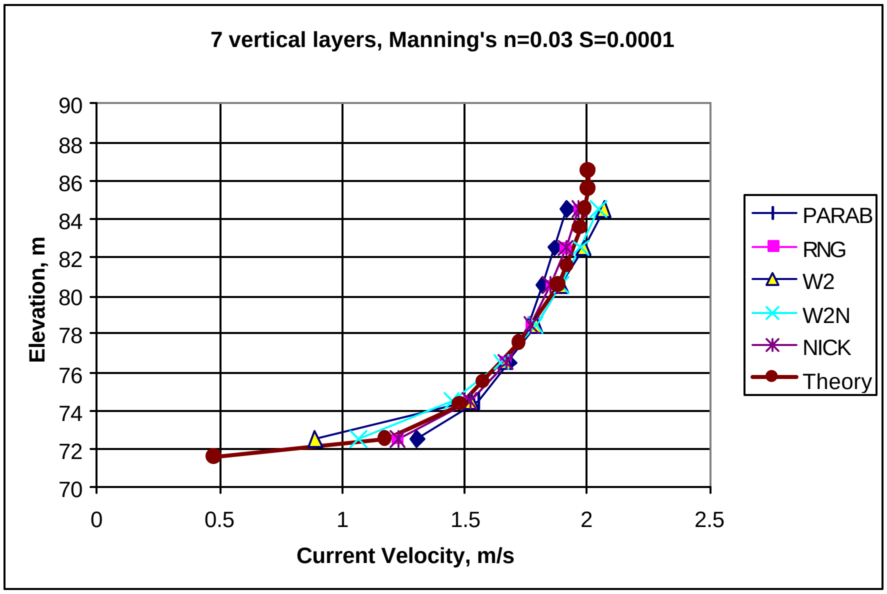

Figure 5. Comparison of vertical velocity predictions of W2 model with various eddy viscosity models compared to theory.

The number of vertical layers significantly affected the model predictions. For example, Figure 6 shows a comparison of vertical velocity profiles from a model with 1, 3 and 7 vertical layers using the PARAB eddy viscosity model.

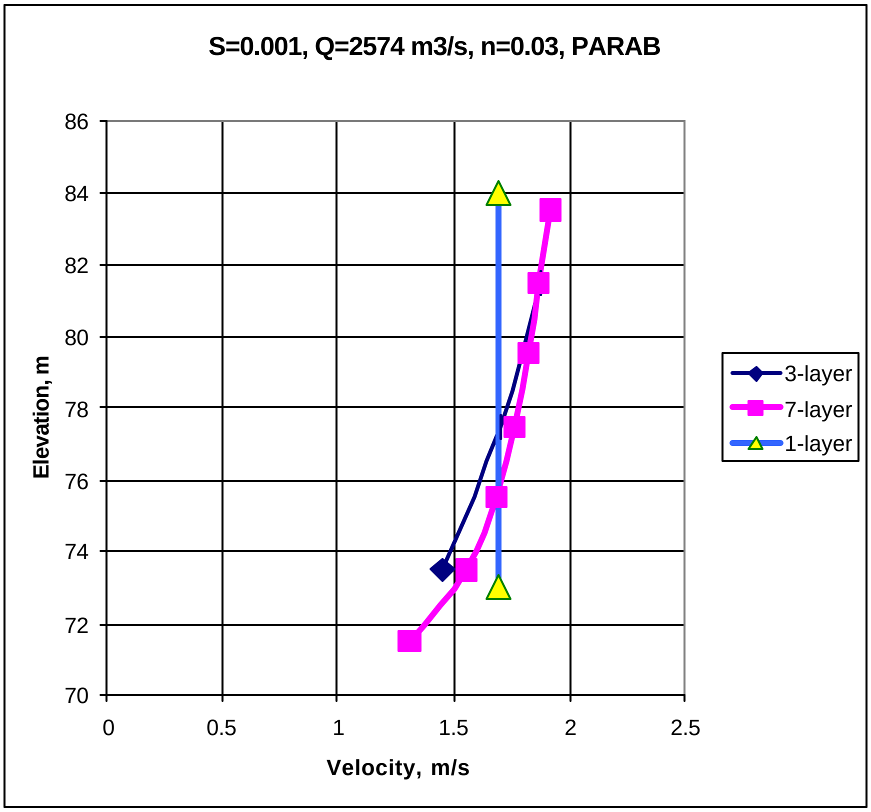

Figure 6. Comparison of vertical velocity predictions of W2 model with 1, 3 and 7 vertical layers.

Figure 7 shows how the change in the number of vertical layers affects the water surface slope over the domain length for a steady-state flow. In order to model the water surface slope of the 1-layer model with the 7-layer model, the apparent value of Manning's friction factor would have to be reduced. Hence, the apparent friction decreases as the number of layers increase.

CE-QUAL-W2 was also compared to the 1-D models DYNHYD (Ambrose et al., 1988) and CE-QUAL-RIV1 (Environmental Laboratory, 1995) by running W2 with only a single vertical layer.

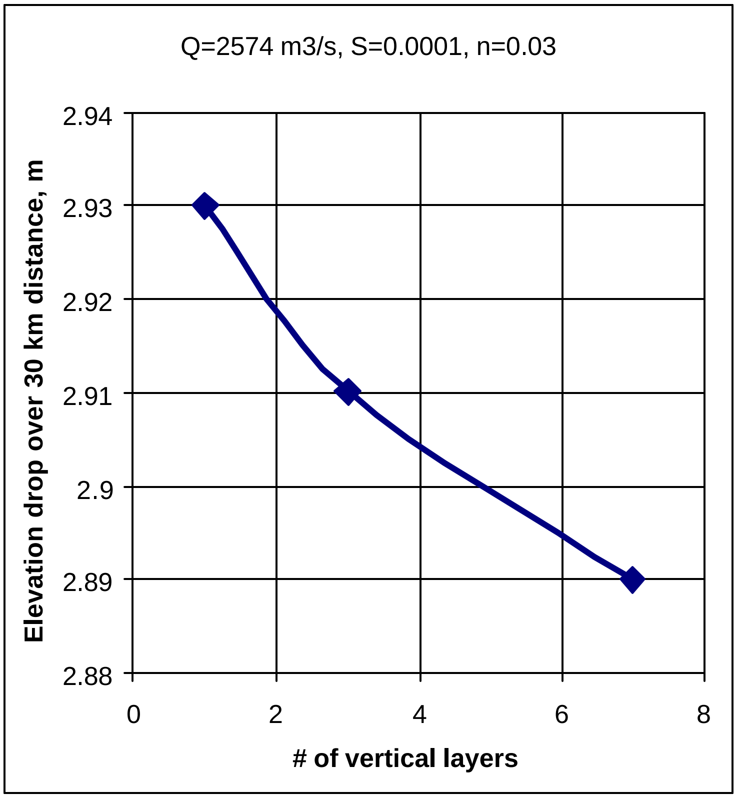

Figure 7. Comparison of elevation drop of W2 model with 1, 3 and 7 vertical layers with same Manning's friction factor.

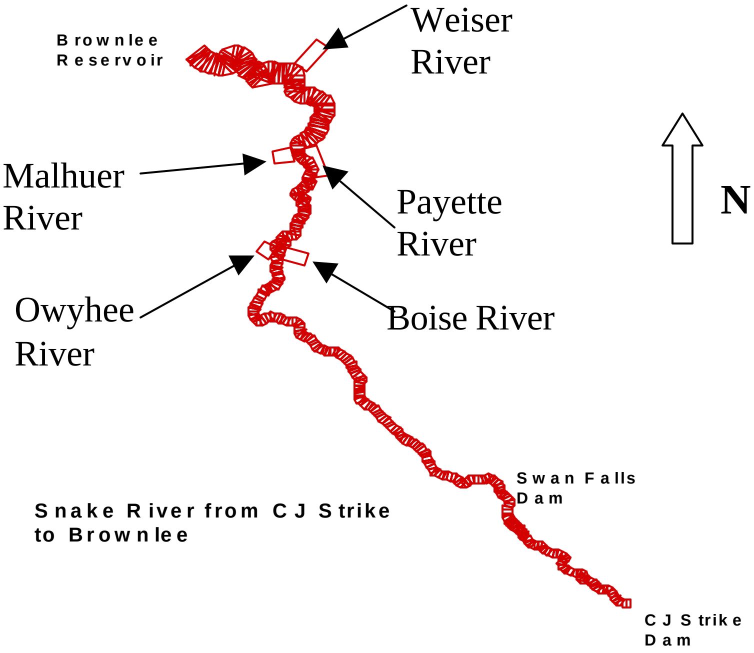

Figure 8. Cell widths (exaggerated) for the LSR between C. J. Strike and Brownlee Reservoir in Idaho, USA.

The average velocities between the 3 models agreed well with theory but the water surface slopes were different. The W2 model predicted an elevation difference of 2.93 m, compared to 2.07 m for DYNHYD and 2.05 m for RIV1 over 30 km for a Q=2574 m^3/s, n=0.03, S=0.001, and channel width=100 m. Based on classical steady-state theory, the actual difference should have been 2.9 m. Both the DYNHYD and RIV1 models required friction factors greater than expected to correspond to classical theory. This may have been a result of these models not incorporating side-wall friction which was important during these test runs where the depth was 15 m and the width was 100 m.

Application to the Lower Snake River

The Lower Snake Model development is documented in Wells and Berger (1998) using CE-QUAL-W2 Version 3. The Lower Snake River from C. J. Strike Reservoir (RM 487) to the headwaters of Brownlee Reservoir (RM 335) is a domain of 152 miles in length. The model consisted of 312 longitudinal segments between 805 and 835 m in length. The segment plan view is shown in Figure 8.

The river was broken into 5 branches of varying slope from 0.001 to 0.0008. The model grid is shown in Figure 9. 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 which experiences a 300 ft drop over its length. The calibrated Chezy values varied from segment to segment between 20 to 80 and were flow and stage invariant.

In contrast to earlier studies using a 1-D river model where the friction factor has to be adjusted according to channel depth or flow rate, the CE-QUAL-W2 Version 3 did not require this adjustment.

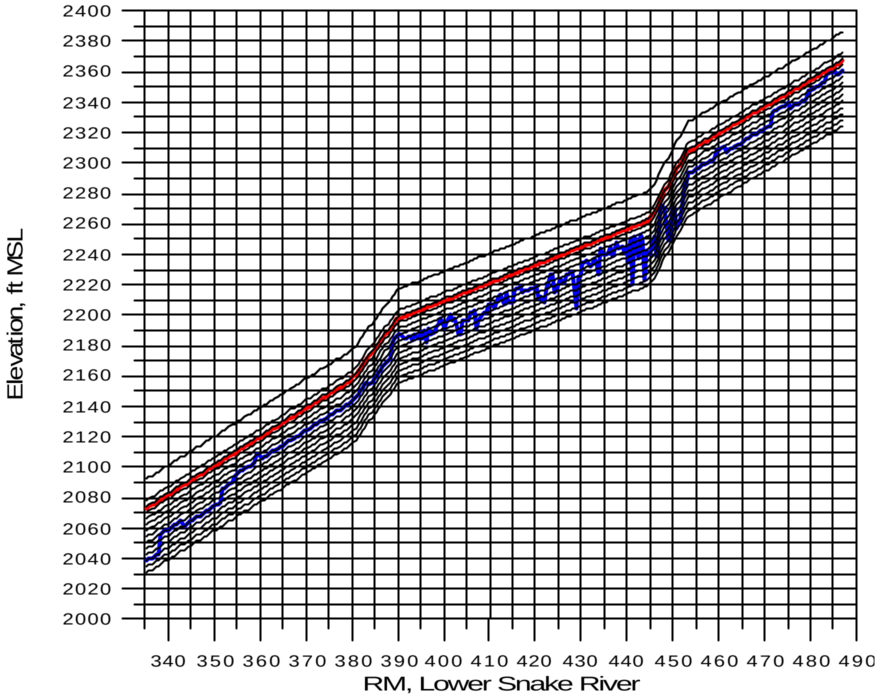

Figure 9. Initial water surface elevation and vertical grid layout superimposed on the channel bottom.

Summary

A 2-D hydrodynamic and water quality model, CE-QUAL-W2 Version 3 was developed for river basin modeling where river and reservoir/lake and estuary systems can be integrated. Further improvements in Version 3 are being explored such as the application of a k-ε turbulence model rather than the existing mixing length model for the vertical transfer of momentum. This 2-D approach, in contrast to 1-D models, allows the use of friction factors which are stage or flow invariant.

Acknowledgments

This research was supported by a grant from the USACE Waterways Experiments Station, Vicksburg, MS. Tom Cole, the project manager, was instrumental in providing advice and insight into CE-QUAL-W2 and guidance for this project.

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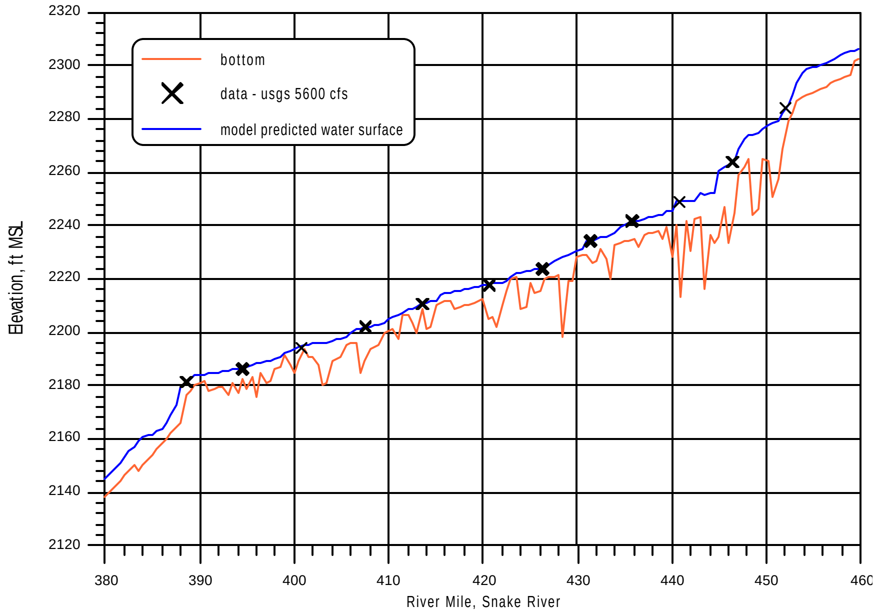

Figure 10. Water surface profile for Lower Snake River at 5600 cfs predicted by CE-QUAL-W2 Version 3.

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