Watershed-Scale Water Quality Modeling in HEC-WAT with CE-QUAL-W2 and HEC-RAS

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Abstract

New software has been developed that facilitates watershed-scale water quality modeling. The U.S. Army Corps of Engineers’ Hydrologic Engineering Center (HEC) has developed a CE-QUAL-W2 plug-in for HEC-WAT (Watershed Assessment Tool) that allows users to import and link multiple CE-QUAL-W2 water quality models with one another as well as with other hydraulic, hydrologic, and water quality models and external time series data. Modelers can create any number of model alternatives to stimulate system-wide water quality for various water management scenarios or time periods. The new software has been deployed by the U.S. Army Corps of Engineers for the Columbia River Treaty (CRT) study. Water temperature and Total Dissolved Gas (TDG) are the key parameters of concern in the Columbia River watershed. The large flows discharged over spillways at the high-head dams in the Columbia River system entrain significant amounts of atmospheric gases. Supersaturated TDG levels can persist for dozens of miles downstream, which can cause gas bubble trauma in fish, with chronic or acutely lethal effects, depending on TDG levels. TDG capability was added to HEC-RAS (River Analysis System) in support of the CRT study to enable existing HEC-RAS models to be linked with the CE-QUAL-W2 models to improve TDG management and impact assessments.

Introduction

Environmental watershed analyses are often performed using multiple water quality models, each of which is targeted to a particular location in the watershed or a particular capability, such as one-dimensional river hydraulics and temperature for a reach or two-dimensional stratified hydrodynamics and eutrophication for a reservoir. To enable efficient watershed-scale assessments, these models need to be integrated into a coherent system, linking flow and/or water quality outputs from one model to one or more downstream models, where appropriate, along with time series from other sources. The U.S. Army Corps of Engineers’ Hydrologic
Engineering Center (HEC) developed the Watershed Assessment Tool (HEC-WAT) to provide a comprehensive systems-based approach to performing water resources studies (HEC 2017). The HEC-WAT software allows modelers to run a sequence of river, reservoir, and watershed runoff models, built for a particular location and purpose, to leverage each model’s individual strengths at geographic scales ranging from a river reach to full coverage of the watershed. The models may be linked together, where one model provides the input for the next model in the computational sequence. For example, HEC-WAT allows a model that is specialized for simulating watershed runoff processes to provide runoff data to models specialized for river or reservoir modeling. Alternatively, any model can be run independently, where HEC-WAT only automates the compute sequence. Whether or not models share data with one another, HEC-WAT provides a common user interface that allows results from all of the models to be analyzed together. This improves the effectiveness of multi-disciplinary teams who need to efficiently analyze a watershed in a systems context.

To be able to compute a model in HEC-WAT and optionally link that model with other models, a plug-in must be developed for the computer simulation program that is used to build and run the model. The plug-in facilitates communication of each model’s inputs and outputs with HEC-WAT. The HEC-WAT modeler controls communication between models using the Model Linking Editor by linking one model’s inputs to the outputs from one or more separate models using each model’s input and output locations. HEC-WAT is configured to connect time series data between models via the HEC Data Storage System (HEC-DSS). In general, users link models by selecting the model locations rather than the specific time series record in the DSS file. However, model inputs can be linked directly to external DSS time series data, which leverages the HEC-DSSVue user interface capabilities.

USACE Northwest Division (CENWD) provided funding and guidance to develop a system water quality model for the Columbia-Snake River watershed utilizing several CE-QUAL-W2 and HEC-RAS (River Analysis System) models. CE-QUAL-W2 (Cole and Wells 2016) is a two-dimensional (2D) laterally averaged hydrodynamic and water quality modeling program, which is widely used to simulate the water quality of reservoirs, lakes, rivers, estuaries, and river basin systems. Furthermore, CE-QUAL-W2 allows modelers to simulate basic eutrophication processes such as temperature, nutrient, algae, dissolved oxygen, organic matter and sediment relationships. HEC-RAS (HEC 2016) is a 1D and 2D river hydraulics model with 1D water quality capabilities. The U.S. Army Corps of Engineers (USACE) and U.S. Bureau of Reclamation (USBR) have developed CE-QUAL-W2 and HEC-RAS water quality models (USACE 2013) to assess the effect of reservoir operations on water temperature and Total Dissolved Gas (TDG) in the Columbia-Snake River watershed. These models are being used to support the Columbia River System Operations (CRSO) Environmental Impact Statement (EIS) and Columbia River Treaty (CRT) projects.

In collaboration with CENWD, Portland State University (PSU), the U.S. Army Engineers Research and Development Center’s Environmental Laboratory (ERDC-EL), and Resource Management Associates, Inc. (RMA), HEC lead development of a CE-QUAL-W2 plug-in for HEC-WAT and updated HEC-RAS and its HEC-WAT plug-in to support water quality modeling within HEC-WAT. The updated software allows modelers to create a basin-scale water quality model, integrating several CE-QUAL-W2 (version 4.2) and HEC-RAS (version 5.0) models in a computational sequence. Moreover, the software allows the flexibility to integrate these models with other hydrologic and hydraulic models. Figure 1 shows the HEC-WAT software with several CE-QUAL-W2 water quality models displayed in an active map schematic to illustrate the ability to create an integrated basin-scale water quality model in HEC-WAT. This schematic shows the plan geometry of several of the Columbia-Snake River CE-QUAL-W2 models. Ongoing software
development is extending the existing water quality capabilities of HEC-RAS, and new water quality capabilities are in development for HEC-ResSim (Reservoir System Simulation) and HEC-HMS (Hydrologic Modeling System). The HEC-WAT plug-ins for these programs will enable integration of these new capabilities with CE-QUAL-W2 and other models within HEC-WAT.

![HEC-WAT user interface, showing CE-QUAL-W2 geometry of the ten Columbia-Snake River models](image)

**Figure 1.** HEC-WAT user interface, showing CE-QUAL-W2 geometry of the ten Columbia-Snake River models

### Integration of CE-QUAL-W2 with HEC-WAT

HEC-WAT plug-ins have been developed for HEC-RAS, HEC-ResSim, HEC-HMS, and HEC-FIA (Flood Impact Analysis). The plug-ins for the HEC software integrate the existing software in HEC-WAT and leverage the software's graphical user interface and capability to read and write DSS files. In contrast to HEC software, the majority of the CE-QUAL-W2 software's time series input and output is via ASCII files. Notably, the parameters and specifications for model setup are defined in an ASCII control file as well a set of ASCII bathymetry files (in fixed-width text or CSV format), one file per waterbody. Therefore, a unique plug-in was developed for CE-QUAL-W2 which included the ability to exchange data with DSS files. In addition, a graphical user interface was developed for the CE-QUAL-W2 plug-in to allow modelers to define initial conditions for flow, water surface elevation, water temperature, and constituent concentrations. The CE-QUAL-W2 software was also updated to generate geometry and geolocation information so the model could be displayed in the HEC-WAT map schematic (Figure 2).
Two components of the plug-in, the Parser and the Data Transformation Tool (DTT), were developed to facilitate communication between individual CE-QUAL-W2 models, the HEC-WAT analysis framework, and other models imported into the HEC-WAT study. The Parser was designed to read and update any setting in the imported CE-QUAL-W2 model’s control file. The Parser provides extensive information for the imported model to HEC-WAT which includes parameter names, units, and filenames. The information provided by the Parser is used to initialize the settings in the CE-QUAL-W2 user interface provided by the plug-in and assist with the exchange of data between the CE-QUAL-W2 ASCII input and output files and the HEC-DSS database used by HEC-WAT. When modelers enter new information in the user interface, the Parser communicates this new information to the CE-QUAL-W2 model’s control file. When the model is computed, any input data linked (using the Model Linking Editor) with an upstream model is first exported (by the DTT) from the upstream model’s DSS output file to ASCII input files using the filenames provided by the Parser. Figure 3 shows a schematic of the compute order. Figure 4 shows a model being computed with the CE-QUAL-W2 software in control of the simulation in progress. Once the CE-QUAL-W2 simulation completes, the DTT imports the time series data from the ASCII output files to the current model’s DSS output file, which can be used by the next model in the computation sequence. The CE-QUAL-W2 plug-in also provides a platform to view the time series data written to DSS, which is plotted by selecting a CE-QUAL-W2 model location in the map schematic. The opened plotting dialog provides options to select and plot multiple time series in one or more sub-plots (Figure 5).
Figure 3. Compute order for the CE-QUAL-W2 plug-in for HEC-WAT. The plug-in processes are shown in orange and blue. The CE-QUAL-W2 executable program is shown in green. Red indicates logging errors and exiting with unsuccessful status.
Figure 4. CE-QUAL-W2 simulation in progress
Integration of HEC-RAS Water Quality with HEC-WAT

To support the water quality modeling capabilities of HEC-RAS within HEC-WAT, the existing HEC-RAS plug-in and HEC-RAS software were modified. HEC-RAS runs unsteady flow and water quality simulations as separate processes, each manually initiated by the user. To automate this process in HEC-WAT, an option was added to HEC-RAS to trigger a water quality simulation after the unsteady flow simulation has completed. A water quality checkbox was added to the HEC-RAS software interface in the “Program to Run” section of the “Unsteady Flow Analysis” dialog to select this option. Second, the capability of HEC-RAS to write water quality output to HEC-DSS was extended to provide the necessary water quality outputs to HEC-WAT so they can be linked with other models. Finally, the HEC-RAS plug-in for HEC-WAT was extended to handle the necessary communication of water quality information, such as providing the list of HEC-RAS water quality parameters to the Model Linking Editor.

TDG Capabilities

In support of the CRSO and CRT projects as well as real-time TDG modeling capabilities, algorithms from the SYSTDG (Schneider and Hamilton 2016a; 2016b) model were incorporated into CE-QUAL-W2 Version 4.2 for “source generation” of TDG at twelve Columbia-Snake River dams. Table 1 lists the five regression equations for calculating spillway flow TDG that were added to CE-QUAL-W2. A number of datasets were used to test and validate the new TDG capabilities. Consequently, the enhancements provide CE-QUAL-W2 modelers with the ability to evaluate the impacts of spill operations and mitigation measures on the tailwater TDG.
Table 1. List of spillway flow TDG production equations in SYSTDG

1. \( TDG_{sp} = P_1 \times (1 - e^{P_3 \times Q_{sp}}) + BP \)
   \( \Delta TDG_{sp} = P_1 \times (1 - e^{P_3 \times Q_{sp}}) \)

2. \( TDG_{sp} = P_1 \times (E_{tw} - E_{ch})^P_2 \times (1 - e^{P_3 \times Q_{sp}}) + P_4 + BP \)
   \( \Delta TGP_{sp} = P_1 \times (E_{tw} - E_{ch})^P_2 \times (1 - e^{P_3 \times Q_{sp}}) + P_4 \)

3. \( TDG_{sp} = P_1 \times (E_{tw} - E_{ch})^P_2 \times q_s^P_3 + P_4 + BP \)
   \( \Delta TGP_{sp} = P_1 \times (E_{tw} - E_{ch})^P_2 \times q_s^P_3 + P_4 \)

4. \( TDG_{sp} = P_1 \times (E_{tw} - E_{ch}) + P_2 \times q_s^P_3 + P_4 + BP \)
   \( \Delta TGP_{sp} = P_1 \times (E_{tw} - E_{ch}) + P_2 \times q_s^P_3 + P_4 \)

5. \( TDG_{sp} = P_1 \times (1 - e^{P_2 \times q_s}) + P_3 \times (Temp_{tw} - P_4) + BP \)
   \( \Delta TGD_{sp} = P_1 \times (1 - e^{P_2 \times q_s}) + P_3 \times (Temp_{tw} - P_4) \)

\( TDG_{sp} \) = spillway discharge total gas pressure (mmHg)
\( \Delta TGP_{sp} \) = spillway discharge gas pressure (mmHg)
\( BP \) = observed barometric pressure (mmHg)
\( E_{tw} \) = observed project (dam) tailwater elevation (feet)
\( E_{ch} \) = project specific tailwater channel elevation (feet)
\( E_{tw} - E_{ch} \) = tailwater channel depth (feet)
\( Temp_{tw} \) = tailwater temperature (°C)
\( Q_{sp} \) = total project spillway discharge (kcfs)
\( q_s \) = flow weighted specific spillway discharge (kcfs)
\( P_1 - P_4 \) = project specific coefficients (unitless)

In SYSTDG, the entrainment of powerhouse flows is computed as a simple linear function of spillway flows. The TDG pressures generated from a project (dam) are computed from the flow-weighted average TDG pressures of the spillway and the powerhouse using the following equation:

\[
TDG_{rel} = \frac{TDG_{sp}(Q_{sp}+Q_{ent}) + TDG_{ph}(Q_{ph} - Q_{ent})}{Q_{ph} + Q_{sp}},
\]

where \( TDG_{rel} \) = project release TGP (Total Dissolved Gas Pressure) after mixing (mmHg), \( TDG_{sp} \) = spillway TGP (mmHg), \( TDG_{ph} \) = release TGP through the powerhouse turbines (mmHg), \( Q_{sp} \) = Total project spill (kcfs), and \( Q_{ph} \) = total flow through powerhouse turbines (kcfs).

Similarly, TDG capabilities were also incorporated into HEC-RAS version 5.0 by adding new algorithms to the existing Nutrient Simulation Module I (NSMI, Zhang and Johnson 2016). The following equation was incorporated into NSMI to leverage its existing dissolved oxygen (DO) and dissolved nitrogen gas (N\(_2\)) simulation capabilities to compute TDG saturation as a derived water quality constituent, which is then reported in the HEC-RAS model output.

\[
TDG\% = \left[ 79 \frac{N_2}{N_2S} + 21 \frac{DO}{DO_3} \right]
\]
In this equation, \( N_2 = \text{dissolved nitrogen gas (mg L}^{-1}) \), \( N_2_s = \text{nitrogen gas saturation (mg L}^{-1}) \), \( DO = \text{dissolved oxygen (mg-O}_2\text{ L}^{-1}) \), and \( DO_s = \text{dissolved oxygen saturation (mg-O}_2\text{ L}^{-1}) \). Version 5.0 of HEC-RAS does not have the capability to compute TDG source generation. However, a future version of the HEC-RAS software will allow modelers to compute advection, diffusion, and reaeration processes for a river reach using input TDG concentrations, such as are currently being provided by the CE-QUAL-W2 program.

**Columbia-Snake River System Model**

The Columbia-Snake River dams and associated water regulation policies have a significant impact on water temperature and TDG. The reservoirs in this watershed typically stratify from the late summer to the early fall and delay the flow of water downstream, altering the spatial-temporal thermal regime of the watershed. Water temperature can affect the timing and survival of adult and juvenile salmon and steelhead migrating through the main-stem Snake and Columbia rivers (NMFS, 2014). The State Departments of Oregon and Washington have identified the Columbia and Snake Rivers as not achieving their temperature standards (EPA 2019a; 2019b).

In addition, the physical characteristics of the dams and the operational procedures can have substantial impacts on the downstream ecosystem. For example, non-turbine releases allow more juvenile salmon to safely pass downstream over spillways (voluntary spill) or during high flow events when turbine capacity is exceeded (involuntary spill). Conversely, dams that allocate large quantities of flow plunging over tall spillways, or other non-turbine outlets, can result in significantly elevated TDG concentrations in the downstream river reaches. High enough TDG concentrations (115% to 120% TDG saturation in shallow water, measured by the twelve highest hours in a 24-hour period) can cause gas bubble trauma or gas bubble disease in aquatic organisms. Above 120% TDG saturation, death occurs before symptoms are shown.

The Oregon State Department of Environmental Quality and Washington State Department of Ecology have developed a Total Maximum Daily Load (TMDL) for TDG for the lower Columbia River (Pickett and Harding 2002), middle Columbia River (Pickett et al. 2004), and lower Snake River (Pickett and Herold 2003). For these river reaches, the measured TDG levels have frequently exceeded TMDL standards. Operational and structural TDG abatement measures (USACE 2016) have been extensively investigated and subsequently implemented, which have reduced TDG levels. Nevertheless, TDG levels frequently remain too high. TDG modeling can help refine reservoir operations and help identify areas for improvement.

In order to further improve the water quality of the Columbia-Snake River watershed, a system water quality model has been built using HEC-WAT to link ten CE-QUAL-W2 and three HEC-RAS models together. This system model includes the main-stem Columbia River from the U.S./Canadian border to downstream of Bonneville Dam, the Snake River downstream of Hells Canyon, and the Clearwater River from Dworshak Reservoir to the confluence with the Snake River. Each CE-QUAL-W2 model represents one of the ten reservoirs in the Columbia-Snake River system, and each model is being used to simulate temperature and TDG for the reservoir, where both the vertical and horizontal dimensions are important. HEC-RAS is being used to represent riverine reaches where a two-dimensional, laterally averaged model is more prone to instability and long run times. HEC-RAS has also been used to represent non-federal dams in the middle Columbia River (the main-stem river reach from the international border with Canada to the confluence of the Columbia and Snake Rivers near Pasco, Washington).
The Columbia-Snake River system model will represent the physical processes that control temperature and TDG in the Columbia-Snake River watershed. Each individual CE-QUAL-W2 or HEC-RAS model has been constructed using measured bathymetry, meteorology, flow, and water quality data to set the initial and boundary conditions. Each of these models has been calibrated and validated, ensuring that the model adequately represents the Columbia-Snake River system. Through the HEC-WAT interface the HEC-RAS and CE-QUAL-W2 models can be used individually or collectively to evaluate water quality changes induced by changes to water management plans.

**Conclusions**

The new CE-QUAL-W2 plug-in and updated HEC-RAS plug-in for HEC-WAT allow users to import and link multiple CE-QUAL-W2 water quality models with one another as well as with other hydraulic, hydrologic, and water quality models and external time series data. Modelers can create any number of model alternatives to simulate system-wide water quality for various water management scenarios or time periods. The CRT study team is using this software to evaluate the impacts on water temperature and TDG due to system operations and configuration of fourteen multiple purpose and related facilities that are operated as a coordinated system within the interior Columbia River basin in Idaho, Montana, Oregon, and Washington. The software can also be used to evaluate watershed-scale eutrophication processes (DO, nitrogen, phosphorus, and algae) and evaluate alternative system operations to improve water quality and ecosystem management in watersheds of varying size and complexity.
References


