# CE-QUAL-W2 Research and Development Project Summary, Ecosystem Management and Restoration Research Program (EMRRP)

## Abstract

There is an increasing demand to include water quality operating objectives in hydrodynamic and water quality reservoir simulation models to improve water management decision-making. Deriving the most effective method to manage reservoir and riverine systems while addressing water quality considerations has emerged in recent years as a significant and complex challenge. Currently, CE-QUAL-W2 functions as a proven and evidence-based two-dimensional (2D) longitudinal/vertical, hydrodynamic and water quality model ([Figure 1](#fig1)). This model was first released by ERDC in 1986 ([Cole and Wells, 2011](#cole-wells-2011)), with more than 300 model applications developed worldwide <https://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/554171/ce-qual-w2/>. CE-QUAL-W2 has been the subject of, or cited by, over 40 journal publications during the past 20 years. For several years ERDC developed and maintained the model continuously, until the 2005 retirement of its original developer, Tom Cole. Although CE-QUAL-W2 has been widely used and applied nationally and internationally, the current version, maintained by the Portland State University (PSU), requires updates based on in-depth research and development activities completed at ERDC. In addition, the model will be significantly enhanced by features that enable CE-QUAL-W2 to be seamlessly linked with other USACE models, such as HEC-RAS, within existing model integration frameworks such as HEC-WAT (Watershed Analysis Tool) and CWMS (Corps Water Management System). These frameworks support system-wide analyses that link multiple models together to accurately simulate different hydrologic domains.

## Purpose

Foundational objectives of this project include:

* Upgrading the current CE-QUAL-W2 model to incorporate the latest water quality modeling research and development conducted at ERDC
* Restructuring the current CE-QUAL-W2 model source code to use robust data storage file formats that adhere to modern standards and are widely and publicly supported, such as HDF5 and JSON. These formats will enable seamless linking with other models such as HEC-RAS and HEC-ResSim, which will significantly improve multi-model system reliability, thus reducing maintenance cost of the software, models, and linked modeling systems.
* Decoupling the water quality component from the hydrodynamics in the current CE-QUAL-W2 model, allowing the water quality simulation to run multiple times with the same hydrodynamic results, eliminating the need for costly repeated hydrodynamic computations
* Updating the technical reference manual and user’s manual
* Releasing a comprehensive version of CE-QUAL-W2 model that has been reviewed by ERDC experts

### Products

Products will include an upgraded Version 5.0 of CE-QUAL-W2, a technical reference manual, and a user’s manual. The latest water quality research and development at ERDC will be incorporated into CE-QUAL-W2 Version 5.0. The current CE-QUAL-W2 model will be restructured to have efficient model data storage formats that allow seamless and reliable linkage with other models such as HEC-RAS and HEC-ResSim. CE-QUAL-W2 Version 5.0 will be developed to meet USACE software requirements. The upgraded version of CE-QUAL-W2 will be released and posted to ERDC’s website for distribution, along with the source code. An updated CE-QUAL-W2 technical reference manual and user’s manual will be available via the website. Journal articles will be developed and published detailing the new model formualtions and validations studies. This will facilitate greater technical peer review and serve as an additional mechanism for technology transfer to the user community. To ensure that annual training is available for USACE personnel, PSU’s CE-QUAL-W2 training workshops will be updated to use the products from this project. EL staff will coordinate training workshops as needed at District offices and/or via webinar.

### Payoff

The updated CE-QUAL-W2 model will support the Corps’ high priority need for environmental assessment, restoration, and management. Incorporation of reservoir operations capabilities will enable water quality and other environmental objectives to influence the reservoir release-decision process. This will improve model accuracy within the reservoir and deliver high quality multi-objective decision-making to achieve ecosystem benefits. Critical downstream habitat will be better managed for water quantity (volume, velocity, depths, etc.) as well as water quality objectives (water temperature, dissolved oxygen, total dissolved gas, etc). Many USACE Districts use CE-QUAL-W2 to perform real-reservoir simulations as part of daily decision support for reservoir releases and assessment of operations for ecosystem restoration. This work unit will develop improved reservoir water quality modeling capabilities that are readily available to those projects, thus reducing the time and cost typically associated with upgrading existing water quality models and implementing new model capabilities. CE-QUAL-W2 has the capability to accurately simulate the conditions that lead to Harmful Algal Bloom (HAB). These conditions include high water temperature, low water depths, sluggish flows, and high nutrient and algae concentrations. The new capabilities in CE-QUAL-W2 will enable multi-objective optimization analyses that will help identify the releases and other management options that could control the occurrence, location, timing, and spatial distribution of HAB’s.

### What is the Problem?

The CE-QUAL-W2 model has been widely used and applied to reservoir systems operated and managed by USACE Districts and other U.S. governmental agencies including the U.S. Bureau of Reclamation (USBR), U.S. Geological Survey (USGS), U.S. Environmental Protection Agency (USEPA), and Tennessee Valley Authority (TVA), as well as numerous state, county, and local agencies <http://www.cee.pdx.edu/w2/>. CE-QUAL-W2 is a legacy model that was not designed to address the current need for watershed-scale, multiple-model studies performed by interdisciplinary teams who need to simulate several alternatives that are optimized for multi-objective decision-making. In addition, the CE-QUAL-W2 model was not designed to work on a system basis, link with current models, or to integrate with current modeling frameworks, databases, and user interfaces. While CE-QUAL-W2 can continue to be used on an individual basis, the current version’s lack of critical features for integrated multi-objective modeling and reservoir operation prevents it from seamlessly and efficiently integrating into current modeling constructs being developed by USACE districts. In addition, USACE Districts are currently relying on Portland State University for ongoing CE-QUAL-W2 development without the indicated supervision, coordination, quality assurance, or review by USACE personnel. For these reasons, the PSU version of CE-QUAL-W2 does not meet USACE software requirements. ERDC will reestablish leadership in developing and maintaining CE-QUAL-W2, while upgrading CE-QUAL-W2 to include the latest ERDC research and development. This will ensure ongoing support and further optimization of a high quality model that meets USACE software requirements in support of District projects and re-establishes ERDC as a leader in water quality modeling.

| A screenshot of a computer  Description automatically generated with medium confidence |
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| *Figure 1. Schematic of a typical CE-QUAL-W2 model, showing the reservoir and riverine sections* |

In recent times, there has been an increasing demand to include water quality operating objectives for water management. Districts need to model physical, chemical, and biological characteristics of water to include the impact of water quality in reservoir system decision-making as it relates to downstream ecosystem habitat. Deriving the most effective method to manage reservoir and riverine systems so that environmental considerations are addressed has emerged in recent years as a significant problem. Within riverine systems such as the Delaware, Missouri, and Columbia River basins there are dozens of reservoirs that influence the water quality of the entire system. Management of large river systems with multiple reservoirs is moving towards a system based approach, and current model development activities need to reflect this. Although CE-QUAL-W2 is a powerful tool and has been widely used and applied across the Nation, the current version does not contain all of the state-of-the-art process descriptions available today. In addition, CE-QUAL-W2 has not been maintained and updated to interface with current riverine models such as HEC-RAS and HEC-ResSim, and their associated user interface frameworks, databases. Linking CE-QUAL-W2 with HEC-RAS and HEC-ResSim will provide a system based capability for meeting water quality objectives in a reservoir and its associated downstream river reach(es) for improved habitat through changes in reservoir operations. The user can evaluate a full suite of operational objectives, test multiple operational rule changes at one or more projects within a watershed, and identify the most beneficial project operations to meet system-wide project and water quality goals.

Many USACE Districts have developed CE-QUAL-W2 model applications for their reservoirs that are being used to answer questions concerning water management impacts on downstream quantity and water quality (e.g., temperature, total dissolved gas, and dissolved oxygen). In particular, the following USACE Districts have used and maintained CE-QUAL-W2 models for their reservoirs: Portland, Seattle, Walla Walla, Savannah, Mobile, Philadelphia, Pittsburgh, Sacramento, Omaha, Kansas City, and St. Paul, just to name a few. CE-QUAL-W2 models maintained by Districts need to be continuously updated to support not only water quality studies but also multi-purpose reservoir operations, planning studies, ecosystem management and restoration, etc.

In order to support a system wide management approach to reservoirs, CE-QUAL-W2 needs to be upgraded to have modern, robust, flexible, extensible, and easily maintained data storage formats for model input and output. Upgrading CE-QUAL-W2 to use these formats will allow CE-QUAL-W2 to seamlessly link with other models and databases for efficient setup, simulation, and evaluation of model results. CE-QUAL-W2 needs to be configured to integrate with these modern frameworks and databases. In addition, the model users have identified the following limitations of the current version of CE-QUAL-W2:

* Inability to model multiple water surface branches simultaneously in an entire water basin
* A carbon cycle module and sediment diagenesis simulation that has been developed at ERDC but not yet incorporated into the current version of CE-QUAL-W2
* Lack of capabilities simulating vertical migration of algae and zooplankton assemblages and smart particle transport
* Multiple model inputs and output files are used in the current version of CE-QUAL-W2, the code requires extensive modifications in order to run efficiently and link with HEC modeling frameworks to evaluate real time waterbody responses to operations and quantify environmental benefits
* Lack of an efficient pre-processor and post-processor

### What are the barriers to solving this problem?

Increasing emphasis on water quality operating objectives for planning eco-system restoration studies and real-time water management has created a need to have an advanced 2D reservoir model in order to evaluate a full suite of environmental objectives in a coordinated fashion and to perform multi-objective planning studies. Hydrodynamics and water quality variations in reservoirs are at the minimum 2D (longitudinal/vertical) in nature. In order to accurately represent the processing of operations and their effects on water quality in river basin reservoirs, a 2D (longitudinal/vertical) hydrodynamic and water quality model like CE-QUAL-W2 is required. The user community has accepted CE-QUAL-W2 as the standard 2D reservoir hydrodynamics and water quality model; however upgrades are needed in the model to reflect current state-of-the-art riverine water quality simulation and to better link with other models and continuously updated real-time data, while effectively integrating with current modeling frameworks, databases, and user interfaces.

### How will you overcome those barriers?

This work will build on the previous development and improvements to CE-QUAL-W2 conducted at ERDC and PSU. To develop this software, ERDC and PSU will work with USACE districts, across the U.S., involved in CE-QUAL-W2 model applications to form an interdisciplinary team. It is expected that team members will interact frequently during the course of the development. This will ensure that relevant needs are adequately considered and addressed from a USACE perspective. Any barriers to the model development will be resolved through discussions and collaboration within the team. In addition, the release version of CE-QUAL-W2 will go through the peer review process and ensure that USACE needs are being met.

### What are the capabilities you are developing?

This project will produce an updated CE-QUAL-W2 (Version 5.0) in support of reservoir operations, assessment, management, and planning studies. In addition, CE-QUAL-W2 will include the latest research and development conducted at ERDC ([Zhang et al., 2015](#zhang-et-al-2015); [Zhang and Johnson, 2016](#zhang-and-johnson-2016)). The following capabilities will be developed and incorporated into the release version of CE-QUAL-W2 Version 5.0:

* CE-QUAL-W2 will be upgraded to directly simulate organic carbon constituents, e.g. refractory dissolved organic carbon (RDOC), labile dissolved organic carbon (LDOC), refractory particulate organic carbon (RPOC), labile particulate organic carbon (LPOC)). In addition, organic nitrogen (e.g. refractory dissolved organic nitrogen (RDON), labile dissolved organic nitrogen (LDON), refractory particulate organic nitrogen (RPON), labile particulate organic nitrogen (LPON), and organic phosphorous (e.g., refractory dissolved organic phosphorous (RDOP), labile dissolved organic phosphorous (LDOP), refractory particulate organic phosphorous (RPOP), labile particulate organic phosphorous (LPOP) will be enhanced. Full carbon, nitrogen and phosphorous cycles can be simulated in the upgraded CE-QUAL-W2. In addition, the simulations of BOD groups (CBOD, NBOD, and PBOD) included in the current version will be reformulated.
* Sediment diagenesis simulation has been incorporated into CE-QUAL-W2 model for both PSU version and ERDC version. This capability needs to be merged and further tested and validated. A final sediment diagenesis module will be incorporated into the release version of CE-QUAL-W2.
* The current version of CE-QUAL-W2 includes multiple input and output (I/O) files with different formats that make the model difficult to seamlessly link with other models. Therefore, the CE-QUAL-W2 I/O formats will be simplified and updated. A code restructuring is necessary to change the I/O formats to facilitate linkage with other models, frameworks, and databases.
* Hydrodynamics and water quality are tightly coupled in the current version of CE-QUAL-W2. The model is ostensibly running on the same grid and time step for hydrodynamics and water quality; however, one must re-run hydrodynamics each time a water quality parameter is changed, even though the water quality parameter change has no effect on hydrodynamics. To overcome this drawback, decoupling the water quality component from the hydrodynamics will be developed. With this approach hydrodynamic simulations are run for a prescribed period, the output is stored, and then it is used as input to multiple water quality simulations.
* Selective withdrawal algorithm will be updated to account for overlapping withdrawal zones for multiple outlets (current model just adds them together).
* The current CE-QUAL-W2 user’s manual will be updated, a technical reference manual and a user manual will be developed to reflect the release version developed under this project.

### Quantitative Metrics

Many USACE Districts have used and maintained CE-QUAL-W2 models for their reservoirs. The final release version of CE-QUAL-W2 will be extensively tested, validated, and documented. Several CE-QUAL-W2 models developed and maintained by the Districts will be selected for the model testing and validation. Under the on-going Columbia River System Operation (CRSO) Environmental Impact Statement (EIS) study, CE-QUAL-W2 models have been developed and calibrated for twelve reservoirs on the Columbia and Snake River system. The project team will collaborate with the District Personnel for the data gathering and model validation.

### Transition Milestones

The updated CE-QUAL-W2, source code and executables, will be released for public distribution from the ERDC and PSU web sites. The updated CE-QUAL-W2 Technical Reference, User’s Manual and Applications Guide will also be available from the web site. In addition, a training course will be provided for USACE Districts and Divisions, other federal and state agencies, and consulting firms.

### Future Work

CE-QUAL-W2’s ability to simulate HAB’s could be extended by adding water quality kinetics algorithms that simulate cyanobacteria concentrations. A major factor in HAB assessment and management is characterizing the vertical location of peak cyanobacteria concentrations in the water column. The hydrodynamics and transport algorithms could be extended to simulate the vertical migration of cyanobacteria, improving the simulation accuracy of conditions that influence HAB formation.