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| --- | --- | --- | --- | --- | --- |
| 1. Submit To:  Director  U.S. Army Engineer Research and Development Center | | | 2. Business Area:  X Civil Works   * Geospatial Research & Engineering * Environmental Quality & Installations * Military Engineering | | |
| 3. Title of Proposed Project: Development of New Capabilities and Enhancements to the USACE Two-Dimensional Reservoir Water Quality Model (CE-QUAL-W2) | | | | | |
| 3.a. Table of Contents:   |  |  | | --- | --- | | Abstract................................................................................................................................................................................ | p2 | | Purpose................................................................................................................................................................................ | p3 | | Background........................................................................................................................................................................ | p4 | | Scope of Work................................................................................................................................................................... | p8 | | Accomplishments to Date............................................................................................................................................ | p11 | | Product Summary........................................................................................................................................................... | p12 | | Work Plan and Cost........................................................................................................................................................ | p13 | | References.......................................................................................................................................................................... | p14 | | | | | | |
| 4. Proposed Total Amount: $1300K | 5. Proposed Duration (in mos): 40 months | | | 6. Start Date (Notice to Proceed): Q3/FY20 | |
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##### Project Development Team (PDT):

* Todd Steissberg (ERDC)
* Billy Johnson (ERDC)
* Zhonglong Zhang (PSU)
* Scott Wells (PSU)
* Chris Berger (PSU)
* John Kucharski (ERDC)
* Barry Bunch (ERDC)
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##### Corps District Collaboration:

* Kathryn Tackley (Portland District)
* Dan Turner (Northwest Division)
* Alexis Mills (Northwest Division)
* Norman Buccola (Northwest Division)
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## Abstract

This work unit was developed in response to a Statement of Need (SON) ENV 1174, presented to the 2018 Environmental Research Area Review Group (ERARG) entitled “Development of New Capabilities and Enhancements to the USACE Two-Dimensional Reservoir Water Quality Model (CE-QUAL-W2),” and to address needs identified in SON ENV 1550, presented to the 2020 ERARG as “Two-Dimensional Water Quality Capabilities for Reservoir Operations Decision-Making.”

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 (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>). 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 (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 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 W2 model to incorporate the latest water quality modeling research and development conducted at ERDC
* Restructuring the current 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 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 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 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 W2 Version 5.0. The current 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. W2 Version 5.0 will be developed to meet USACE software requirements. The upgraded version of W2 will be released and posted to ERDC’s website for distribution, along with the source code. An updated 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 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 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.

## Background

### What is the Problem?

The 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/). 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 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 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 W2 development without the indicated supervision, coordination, quality assurance, or review by USACE personnel. For these reasons, the PSU version of W2 does not meet USACE software requirements. ERDC will reestablish leadership in developing and maintaining W2, while upgrading 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.

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| Figure1.png |
| *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 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, 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 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 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 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. 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, W2 needs to be upgraded to have modern, robust, flexible, extensible, and easily maintained data storage formats for model input and output. Upgrading W2 to use these formats will allow W2 to seamlessly link with other models and databases for efficient setup, simulation, and evaluation of model results. 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 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 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 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 W2 is required. The user community has accepted 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 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 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, 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:

* 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 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 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 W2.
* The current version of 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 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 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 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 W2 models for their reservoirs. The final release version of W2 will be extensively tested, validated, and documented. Several 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, 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 W2, source code and executables, will be released for public distribution from the ERDC and PSU web sites. The updated 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. Endorsements:

* Kathryn Tackley (Portland District)
* Dan Turner (Northwest Division)
* Steve Juul (Walla Walla District)
* Brian Zettle (Mobile District)
* Rose Reilly (Pittsburgh District)
* John Hargrave (Omaha District)
* Tony Clyde (Tulsa District)

### Other Work Package Attributes:

This project will be a continuation of research and development efforts funded under previous Environmental Laboratory Water Quality Research Programs. CE-QUAL-W2 has been developed by the Environmental Laboratory (EL) and Portland State University (PSU). The new Versions 4.3 and 5.0 of CE-QUAL-W2 developed under this work unit will supercede all previous versions of CE-QUAL-W2 on the official USACE approved software list. EL will maintain all rights and responsibilities for distributing, maintaining, and updating CE-QUAL-W2 v4.3 and 5.0, with continued assistance from PSU.

## Scope of Work

This project will be conducted by a team of scientists and engineers from ERDC and PSU. The specific technical tasks are:

### Task 1 - Upgrade water quality kinetics

This task will incorporate the new capabilities developed at ERDC-EL into the current version of CE-QUAL-W2 maintained by PSU. A full carbon cycle with nitrogen and phosphorous cycles has been developed and integrated into previous version of W2 at ERDC ([Figure 2](#fig2)). In addition, the simulations of BOD groups (CBOD, NBOD, and PBOD) included in the current version of W2 will also be reformulated to ensure that these constituents are appropriately simulated. This feature will be migrated into the current version. In addition, a sediment diagenesis module has also been developed and included into the previous version. This capability needs to be merged into the updated version and further tested and validated. A final sediment diagenesis module will be incorporated into the release version.

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| Figure2.png |
| *Figure 2. Carbon, nitrogen, and phosphorous cycles simulated in W2.* |

Additional water quality capabilities currently developed and in a research version will also be further developed and added into the updated W2.

* USACE Team:
  + Todd Steissberg (EL)
  + Billy Johnson (EL)
* External Collaborators:
  + Zhonglong Zhang (PSU)
* Products:
  + CE-QUAL-W2 Version 4.3 Release, Q2/FY21

### Task 2 - Upgrade model input and output

The current version of W2 includes multiple data storage files for model input and output (I/O), each with a different custom-developed format. These files make the model difficult to seamlessly link with other models. Therefore, W2 data storage formats will be upgraded. A code restructuring is necessary to change the storage formats. Many numerical models write self-describing binary files such as NetCDF or HDF, from which data can be efficiently accessed via free and open source tools, such as HDFView. The file that contains the settings for each model application contain over 200 records and thousands of variables. The current format is extremely fragile and easy to break. This regularly costs modelers hours to diagnose and fix minor model setup errors. When W2 models have been linked together in automated systems, such as HEC-WAT, extensive problems have been encountered, leading to severe project delays. Simply switching to a modern format, such as JSON, creates a reliable storage system is that is robust and can be easily validated. JSON is very widely used in Internet, desktop application, and mobile device software and adheres to a standard. Software now exists to allow harvesting into data catalog systems designed to service a broad range of users, enable non-expert users to visualize model outputs, map model results, and compare with field data and with other models. In addition to serving output data sets, input datasets are also being consolidated into a single file system, so users can easily examine input parameters and boundary conditions. A utility will be developed to import previous W2 model inputs into the new data storage formats for the updated version.

* USACE Team:
  + Todd Steissberg (EL)
  + Billy Johnson (EL)
* External Collaborators:
  + Zhonglong Zhang (PSU)
  + Scott Wells (PSU)
  + Chris Berger (PSU)
* Products:
  + CE-QUAL-W2 Version 5.0 Alpha, Q2/FY22

### Task 3 - Develop Python/Jupyter Model framework and plotting capabilities

A framework will be developed using Python that links CE-QUAL-W2 with modern scientific Python libraries, which will allow developing new input/output capabilities and plotting analysis capabilities. Plotting capabilities will be developed to visualize the project bathymetry files, water quality and hydrodynamic time series, and 2D contour plots of reservoir water quality profiles. A prototype Jupyter notebook will be developed to link the capabilities together to create a simple documented user interface. This interface will be updated and extended during completion of the subsequent tasks.

* USACE Team:
  + Todd Steissberg (EL)
  + John Kucharski (EL)
* External Collaborators:
  + Zhonglong Zhang (PSU)
* Products:
  + Python framework, Q1/FY21
  + Prototype Jupyter notebook, Q1/FY21
  + Plotting capabilities, Q1/FY21

### Task 4 - Develop reservoir operations capabilities

USACE dams are typically designed to serve multiple objectives, including flood protection, water supply for municipal and agricultural needs, hydropower generation, navigation, recreation, and ecosystem restoration and management, which includes water quality objectives. Dam operation can have adverse effects on downstream water quality and ecosystem properties. The current version of W2 depends on specified outflow time series, which are usually derived from other models that do not accurately capture the releases that best meet various water quality objectives. W2 needs to be able to compute reservoir releases, considering water quality and other environmental objectives, balanced against objectives for flood control, hydropower, navigation, water supply, and navigation. Reservoir operations capability will be developed that will enable multi-objective release-decision making that incorporates water quality and other environmental objectives into the decision-making process. This capability will be incorporated into W2 to examine dam flow control impacts on downstream water quality and to determine how downstream objectives will be met in terms of temperature and water quality. With this new feature, W2 will be capable of examining impacts of dams and flow regulation on downstream temperature and water quality conditions as well as identifying how operations may be improved for ecosystem benefits.

* USACE Team:
  + John Kucharski (EL)
* External Collaborators:
  + Zhonglong Zhang (PSU)
* Products:
  + Reservoir operations capabilities, Q4/FY21

### Task 5 - Upgrade hydrodynamic and water quality computation engine

Hydrodynamics and water quality are tightly coupled in the current version of W2. The model is ostensibly running on the same grid and time step for hydrodynamics and water quality. However, modelers must re-run hydrodynamics each time a water quality parameter is changed, even if the water quality parameter change might have no effect on hydrodynamics. The coupling of hydrodynamics and water quality are a current advantage of the CE-QUAL-W2 framework compared to other codes which do not couple them. One example is where water quality state variables affect the density regime and therefore affect hydrodynamics. In cases the water quality state variable does not impact hydrodynamics, decoupling of the water quality component from the hydrodynamics in W2 will be developed thus increasing computational efficiency. With this approach hydrodynamic simulations are run for a prescribed period, the output is stored, and then it is used as input for multiple water quality simulations. One benefit is that the water quality simulation can be run multiple times with the same hydrodynamic results, eliminating the need for repeating costly hydrodynamic computations if the water quality state variables do not affect the density regime.

The current version does not solve the water surface in all the model branches simultaneously in an entire water basin. A simultaneous equation solution of the water surface in all branches will be implemented for the updated model. In addition, the hydrodynamic stability of the riverine segments will be improved.

To better support increasing demand to include water quality operating objectives for water management, selective withdrawal algorithm will be updated to account for overlapping withdrawal zones for multiple outlets (current model just adds them together). Additionally, the project team will evaluate using multi-core processing capability emphasizing numerical precision of simulations at the expense of fast code execution, continue development on using trapezoidal grid cells rather than rectangular cells.

* USACE Team:
  + Todd Steissberg (EL)
  + Billy Johnson (EL)
* External Collaborators:
  + Zhonglong Zhang (PSU)
  + Scott Wells (PSU)
  + Chris Berger (PSU)
* Products:
  + CE-QUAL-W2 Version 5.0 Beta, Q2/FY23

### Task 6 - CE-QUAL-W2 v5.0 final version with documentation

The final release version of CE-QUAL-W2 v.5.0 will be prepared and posted to the ERDC website for release. A case study will be conducted and documented in a technical note to demonstrate all capabilities included in the final release version of W2. The updated W2 Technical Reference Manual and User’s Manual will be posted to ERDC’s web site. A final webinar will be prepared using the case study and presented to USACE District and Division staff, including water quality modelers and managers.

* USACE Team:
  + Todd Steissberg (EL)
  + Barry Bunch (EL)
* External Collaborators:
  + Zhonglong Zhang (PSU)
* Products:
  + CE-QUAL-W2 Version 5.0, Q4/FY23
  + User’s Manual, Q4/FY23
  + Technical Reference Manual, Q4/FY23
  + Technical Note, Q4/FY23

## Accomplishments to Date

### Team Building

Team members were identified. Multiple conference calls were held to discuss various aspects of the proposal and to refine the focus of the development. A kick-off meeting will be held via WebEx in June 2020.

### Preliminary Site Selection

Several W2 projects will be used to test and validate the newly developed and updated version of W2. Potential W2 projects may include Reservoirs on the Columbia River and Missouri River, Snake River, Lower Minnesota River. The site section will be finalized by the PDT in FY20.

## Product Summary

Products associated with each of the described tasks and target delivery dates are summarize in [Table 1](#tab1), below. For training, it is anticipated that products from this work unit will be incorporated into the existing PSU CE-QUAL-W2 workshop and that ERDC will investigate developing a USACE Prospect Course. Given that CE-QUAL-W2 is an engineering model, the PDT will work to ensure that the new version is on the USACE’s list of approved models.

*Table 1. Products and delivery dates*

| **Task** | **Products** | **Date** |
| --- | --- | --- |
| 1 | CE-QUAL-W2 Version 4.3 | Q2/FY21 |
| 2 | CE-QUAL-W2 Version 5.0 Alpha | Q2/FY22 |
| 3 | Python Framework  Prototype Jupyter Notebook  Plotting Capability | Q1/FY21  Q1/FY21  Q1/FY21 |
| 4 | CE-QUAL-W2 Operations Capability | Q4/FY21 |
| 5 | CE-QUAL-W2 Version 5.0 Beta | Q2/FY23 |
| 6 | CE-QUAL-W2 Version 5.0 Final  User's Manual  Technical Reference Manual  Webinar  Technical Note | Q4/FY23  Q4/FY23  Q4/FY23  Q4/FY23  Q4/FY23 |

### 

## Work Plan and Cost

The project will extend over 40 months from Q3/FY20 to Q4/FY23. Major tasks and milestones are listed in [Table 2](#tab2) below.

*Table 2. Project schedule*

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A total level of effort of $1,300,000 is proposed. Estimated costs by task ([Table 3](#tab3)) and by organization ([Table 4](#tab4)) are summarized below.

*Table 3. Project budget by task ($K)*

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*Table 4. Project budget by organization ($K)*

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### Contracting Actions

* FY20: Portland State University - $150K ($100K Contract, $50K Burdens)
* FY21: Portland State University - $300K ($200K Contract, $100K Burdens)

## References

Cole, T.M., Wells, S.A., 2011. *CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model*, Version 3.71, Portland State University, Portland, OR.

Zhang, Z., Sun, B. and Johnson, B.E. 2015. “Integration of a benthic sediment diagenesis module into a two-dimensional hydrodynamic and water quality model - CE-QUAL-W2”. *Ecological Modelling*, 297:213-231.

Zhang, Z., Johnson, B.E., 2016. *Aquatic Nutrient Simulation Modules (NSMs) Developed for Hydrologic and Hydraulic Models*. ERDC/EL TR-16-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS.