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| From: | **Taeyun Kim and Tarang Khangaonkar - PNNL** |
| Subject: | **Progress in the Development of Offline Linkage between CE-QUAL-ICM and FVCOM** |

***Background***

Pacific Northwest National Laboratories (PNNL) is currently developing a hydrodynamic and water quality model of the Pacific Northwest Coastal waters including Puget Sound and the Straits along U.S.-Canada border in the state of Washington. This work is being conducted collaboratively with U.S. EPA and Washington State Department of Ecology (Ecology). The objective of the study is to develop a predictive water quality model of the system including nutrients and phytoplankton dynamics to help in planning restoration actions and effluent loading and treatment requirements for the future. Ecology and U.S. EPA are looking to use this tool to address various management questions such as “How much nutrient loads can Puget Sound Assimilate”?

Through a contract with U.S. ACE, University of Massachusetts (U. Mass) had begun developing a linkage between their FVCOM hydrodynamic model and the U.S.ACE water quality model CE-QUAL-ICM. Based on local Puget Sound experience, PNNL concluded that this offline linkage between FVCOM and CE-QUAL-ICM provides an ideal modeling system for the type of fjordal water body that Puget Sound is and the nature of problems that are currently being addressed by various groups in the Pacific Northwest.

Upon contacting U.S.ACE we received the associated files and a document prepared by U. Mass which explained the progress status including a list of additional activities that needed to be completed and tested before linkage could be considered ready for application. PNNL continued the work of developing the linkage code and attempted to complete the task through testing of the code against analytical solutions. We believe the work is nearly complete with a couple of items that require attention and could be addressed as next steps.

PNNL is pleased to resubmit the files back to U. Mass with our appreciation for developing this powerful code. We are happy to participate in this development as collaborators. Contributions made by PNNL to this development are listed below.

***A Summary of PNNL Contribution and Modifications to FVCOM-CE-QUAL-ICM Linkage Files***

Based on our review of the files and documents provided by U.S. ACE and U. Mass, we understood that the initial steps completed in developing the linkage by U. Mass were as follows.

* All common blocks from the modules in CE-QUAL-ICM were deleted
* Subroutines were re-written and compiler tests were conducted
* New makefiles were recreated and tested
* A NetCDF format module of FVCOM that can directly be adopted by the CE-QUAL-ICM model was created
* Subroutines in modified CE-QUAL-ICM that read the input file from NetCDF FVCOM output files were written

Upon receipt of files from U.S. ACE, PNNL attempted to compile and run the FVCOM and CE-QUAL-ICM offline linkage model (linkage code). Even though the linkage code could read FVCOM output files, the solutions generated did not appear to be correct. PNNL then proceeded to conduct the following activities to systematically understand the operation of the linkage code, and implement modifications to take the linkage to completion.

* *Examination of the linkage code using a simple test case*
* First, we overhauled the files, checked blocks and arrays, and deleted unnecessary input file and variables
* We then created a simple flow channel using a test (triangular cell) mesh and computed corresponding flow field using FVCOM model
* We examined whether the linkage code was able to correctly read the flow field
* *Modification of appropriate subroutines to complete the linkage code*
* The linkage code could not be applied to the above channel case directly. This was because the linkage code at that point did not include river/open boundary features. We modified the code and added subroutines, such as wqm\_inputs.f, wqm\_main.F, wqm\_init.F, bcond\_wqm.F, adv\_wqm.F, fct\_nut.F, hydro.F, mod\_obcs.F, vdif\_wqm.F. We also recognized that the linkage code would require many variables from FVCOM model in order to solve transport of water quality constituents. To enable this, we modified various subroutines, including ncdio.F, mod\_obcs.F, bcond\_wqm.F, and also added more variables to NetCDF FVCOM output files.
* *Debugging of the linkage code*
* This required considerable iterative effort. Using the test mesh, we applied the linkage code examined water quality variables to identify the potential errors.

***Testing of FVCOM-CE-QUAL-ICM linkage code***

To examine the performance of FVCOM-CE-QUAL-ICM offline linkage model (linkage code), we applied the linkage code to simple tests with known analytical solutions. These included a pulse, a plume, and a BOD/oxygen drawdown, Nutrients and Phytoplankton interaction. The linkage code results were compared with their known analytical solutions.

* *Pulse Test*– To demonstrate the transport of water quality state variables, we used a long channel mesh with 1,592 triangular elements and 1,000 nodes. The horizontal resolution was 25 m by 200 m in the x and y direction respectively. Three layers were employed with 1 meter depth in each layer. Initial concentration was set to 0 everywhere except at the pulse line source with a width of 4,000 m and a concentration of 20. The flow was a uniform in x direction with a constant velocity of 2 m/sec.
* *Effluent Plume Far-field Dilution Using Brooks 4/3rd Law* –To test the advection and diffusion of water quality state variables, we used a fine mesh with 50,000 triangular elements and 25,551 nodes. The horizontal resolution was 20 meters and three layers were employed with 5 meter depth in each layer. Initial concentration was set to 0, and the flow was specified as uniform direction (x-direction) and with a constant velocity of 2 cm/sec. The plume source was located at the center mesh of y-axis and its initial concentration was 20.
* *BOD/oxygen drawdown & Nutrients and Phytoplankton* - To validate water quality state variable kinetics, and especially the interaction of nutrients, DO, and phytoplankton, we conducted the classic “Streeter-Phelps” DO/BOD sag and the phytoplankton growth/nutrient drawdown per example in Thomann and Mueller (1987).

The linkage model results for the above test cases matched analytical model solutions well. The linkage model appears ready for application to a real waterbody. Recommendations for continuing improvements are listed in the following section.

***Recommendations for Additional Improvement***

1. *Model Performance at the Ocean Open Boundary.* There remains an over/undershoot issue for the water quality variables at the boundary which we have tested several ways and still have not resolved. Also, note that in its current state, the water quality equations were streamlined to match the analytical solution for a sewage outfall and its effects on phytoplankton growth and nutrient drawdown as described in Thomann and Mueller (1987). They would need to be re-set to their original form.
2. *Parallel Mode version*. The linkage code in its present state is not parallelized. We are currently running the code on a single processor. Given the interest in assessing long-term changes of water quality state variables over large area (Like Puget Sound) with fine resolution, there it is essential to parallelize theFVCOM-CE-QUAL-ICM linkage.

***FVCOM and CE-QUAL-ICM Linkage Files***

Contents of the Zip File

\code -- FVCOM-CE-QUAL-ICM linkage code

\input Netcdf -- FVCOM output files

\Run – Initial and boundary input files and a job file.