An Implicit 2-D Depth-Averaged Finite-Volume Model of Flow and Sediment Transport in Coastal Waters

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Abstract

An implicit finite-volume scheme with several advanced techniques has been applied to solve the depth-averaged 2-D shallow water flow equations. This model uses an unstructured multiple-level quadtree (telescoping) rectangular mesh, which can locally refine the mesh around structures or in high-gradient regions by splitting a coarse cell into four child cells and using as many levels of refinement as necessary, as shown in Figure 1. This quadtree mesh can improve the accuracy of the model with a relatively small increase in number of cells. The grid points are numbered by means of an unstructured index system, so that the mesh can be as flexible as triangular mesh while it has the merits of the traditional rectangular mesh.

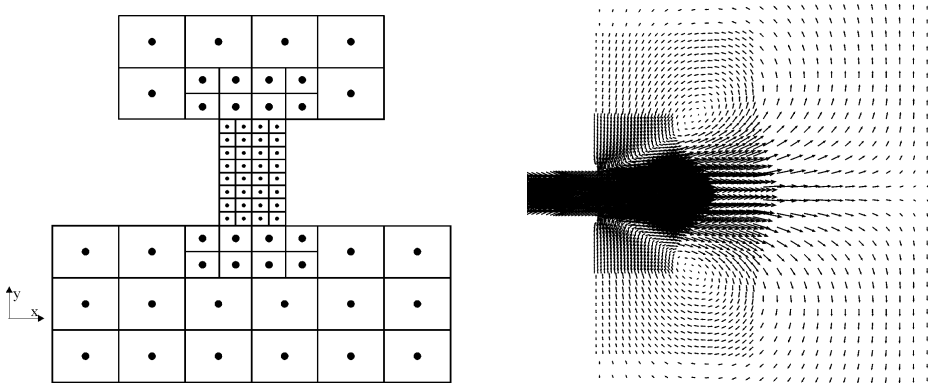

Figure 1. (left) Sketch of quadtree mesh system; (right) Flow near an idealized inlet during flood tide simulated using the developed model on a quadtree mesh

The model uses the non-staggered (collocated) system, in which primary variables u-, v-velocity, and water level are stored on the same set of grid points, so that the computer code can be relatively simple and require less memory and the interface between fine and coarse cells can be easily handled. The convective terms in the momentum equations are discretized using one of several upwinding schemes, including the hybrid upwind/central difference, exponential difference and HLPA schemes. The HLPA scheme has second order accuracy in space, while the other two schemes have the accuracy between first and second orders. The SIMPLEC algorithm with under-relaxation is used to handle the coupling of water level and velocity and achieve high numerical stability and efficiency. Fluxes at cell faces are determined using the Rhie and Chow's

momentum interpolation method, to avoid spurious checkerboard oscillations. Because the mesh is unstructured, the discretized algebraic equations have sparse, asymmetric matrices of coefficients. These equations are solved iteratively using the flexible GMRES method with ILUT preconditioning, which is one of the best choices available in the literature for solving such algebraic equations.

The developed model uses several turbulence models, such as depth-averaged parabolic eddy viscosity model, modified mixing-length model, and modified subgrid model, taking into account the eddy viscosity resulting from current, wave propagation, and wave breaking. The model also considers the effect of both waves and current on the bottom friction. It has two-way coupling between flow and the steady-state spectral wave transformation model CMS-Wave. It takes the wave radiation stresses simulated by the wave model as a forcing source in the momentum equations. A well-developed longshore current profile is assumed at each cross-shore boundary, so that the simulation domain along the coast can be shortened and the model efficiency can be enhanced.

The model simulates the non-equilibrium transport of total load (sum of suspended load and bed load) with multiple size classes (if needed) and the resulting morphology changes. The sediment transport model solves the convection-diffusion equation with the same finite volume method on the quadtree rectangular mesh as that used by the flow model. The sediment transport capacity is determined with one of the Watanabe formula, Lund-CIRP formula, and van Rijn formula. The model can handle hard bottom and bottom avalanching efficiently.

The model has been extensively tested using laboratory and field measurement data. The developed numerical algorithms handle well the flow continuity and smoothness between fine and coarse grids in the quadtree mesh, as shown in Figure 1 (right). In particular, it has been quantitatively validated against field measurements of currents and water levels at Gironde Estuary, France and Grays Harbor, U.S.A., Figure 2 compares the measured and simulated water levels and velocities at Station Richard in the case of Gironde Estuary. In the case of Grays Harbor, the severe storm of February of 2006 is simulated with a 30-min time step to demonstrate the stability of the model under extreme forcing of 8-m waves and 22-m/sec wind. The developed model is robust and reliable and has the potential to be used in simulation of long-term flow and morphodynamic processes in coastal waters.

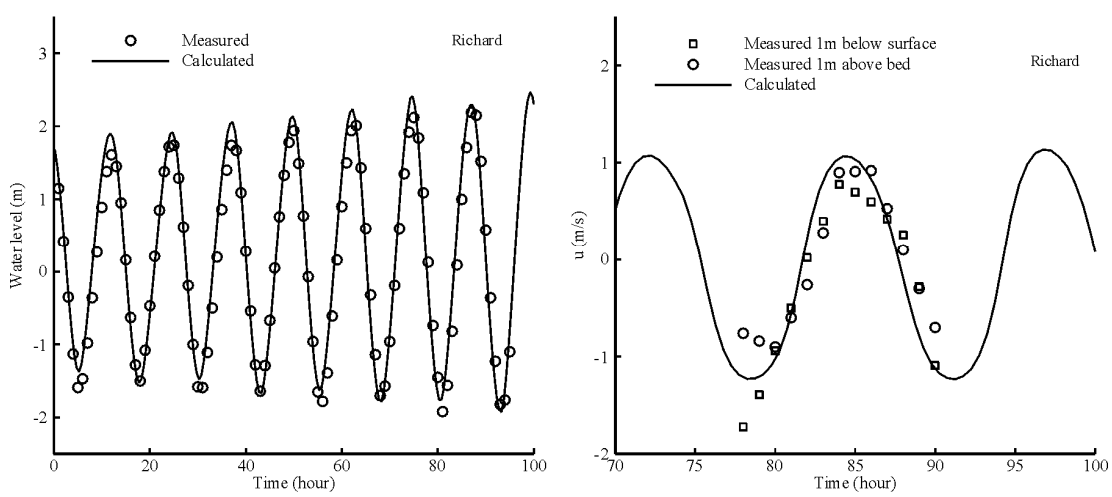

Figure 2. Measured and simulated water levels and velocities in Gironde Estuary