Numerical modelling of hydrodynamic and solute transport processes in shallow water environment

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Abstract

This thesis studies the numerical modelling of a range of hydrodynamic, solute transport and biochemical reaction processes in shallow water environment, combining both Euler and Lagrangian techniques. The research consists of two parts: the rapid flow modelling and the solute transport modelling.

In the rapid flow modelling, the research is focused on demonstrating the impact of modifying the Boussinesq coefficient when simulating rapid flows in various situations. The traditional Alternating Direction Implicit (ADI) scheme has been proven to be incapable of modelling trans-critical flows. Its inherent lack of shock-capturing capability results in spurious oscillations and computational instabilities. However, the ADI scheme is still widely adopted in flood modelling software, and various special treatments have been designed to stabilise the computation. Modification of the Boussinesq coefficient to adjust the amount of fluid inertia is a numerical treatment that allows the ADI scheme to be applicable to rapid flows. A comprehensive study has been undertaken to examine the impact of this numerical treatment over a range of flow conditions. A shock-capturing TVD-MacCormack model is used to provide reference results.

In the solute transport modelling, a mesh-free, depth-averaged and highly robust random walk model has been developed for simulating the two-dimensional solute transport processes. The development of the random model consists of two stages. In the first stage, extensive parametric studies have been undertaken to investigate the influences of the number of particles, the size of time steps and the technique of sampling processes used in the random walk model. The model is then applied to investigate the solute oscillation along a tidal estuary subject to extensive wetting and drying during tidal oscillations. The flow velocities are interpolated from the grid-based TVD-MacCormack flow solver. Finally, the model is applied to investigate wind-induced chaotic mixing in a circular shallow basin. The effect of diffusive processes on the chaotic mixing is investigated. The results of the first stage research provide a guideline for properly presenting the outputs of the random walk method for scientific analyses. In the second stage, the random-walk model is further developed to investigate the advection, diffusion and reaction processes of non-conservative materials. First, several classical test cases are presented to showcase the capability of the random walk model in addressing the problem of continuous release of non-conservative substances. Then, the method is applied to model the BOD-DO balance along a hypothetical river. The numerical results are in good agreement with the analytical solution. Finally, the developed scheme is used to study the pollutant transport in Thames Estuary. The current model is illustrated to be able to accurately predict the interaction between multiple pollutants in real-world situations with uneven bathymetry and extensive intertidal floodplains.