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Numerical modelling of gravel-bed river morphodynamics

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Abstract

This thesis is about the development and testing of a novel two-dimensional numerical model (the GIAMT2D model) able to address the hydro-morphodynamic evolution of gravel-bed rivers.
The model solves the two-dimensional hyperbolic system of partial differential equations (PDEs) arising from the shallow water-Exner model, describing free surface shallow flows over erodible bed, with suitable closure relations for bedload transport. A coupled formulation of the mathematical problem, which is needed in order to correctly handle sediment transport in Froude trans-critical flow conditions, is implemented, resulting in a non-conservative hyperbolic problem, which requires the adoption of a path-conservative scheme.
A drawback of the fully-coupled shallow water-Exner model is that in general the solution of the Riemann problem is not easily available, at least if complex empirical sediment transport formulae are applied, which makes the upwind approach inadequate for designing numerical approximations to the solutions. Adoption of the more general, Riemann solver-free centred approach is thus required, the drawback being that centred schemes are significantly less accurate than upwind schemes in some specific cases, namely for intermediate waves and computations at low CFL number. In GIAMT2D an original centred upwind-biased scheme (UPRICE2-Cd) is applied, recovering accuracy typical of upwind methods, still being able to include any bedload transport formula. The proposed scheme results from original studies in applied mathematics, presented in the first part of the thesis, concerning the development of upwind-biased variations of the centred FORCE scheme for the solution of hyperbolic systems of PDEs, in conservative and non-conservative form. The performance of these schemes is thoroughly assessed in a suite of tests for the shallow water equations.
The GIAMT2D model embeds the UPRICE2-Cd scheme extended to second-order accuracy in the ADER framework, inserted in a robust second-order preserving splitting technique for the treatment of frictional source terms, and includes an

original wetting-and-drying procedure. The model performance is checked in well-established classical test cases with fixed and movable bed.
These applications highlight the capability of the model in correctly and accurately solving the equavtions in various cases, e.g. in computations at low local CFL, in the solution of wet-dry fronts with fixed and movable bed and in the prediction of sediment transport in Froude trans-critical conditions.
The concept of "morphodynamic benchmark" is introduced for the purpose of assessing the model performance in reproducing basic river morphodynamic processes for which established theoretical and experimental knowledge is available. Unit processes with utmost importance for gravel-bed river morphodynamics, like free and forced bar instability and the stability of channel bifurcations, are chosen for this aim. In this novel approach for assessing the model capabilities, the numerical solutions satisfactorily compare with approximate analytical morphodynamic solutions and laboratory data.
Having proved that the model is able to reproduce the salient features of these classical morphodynamic solutions, an original morphodynamic study is finally carried out, concerning the non-linear interaction of free and forced bars in straight channels, for which a mature analytical theory is not available at present. The numerical runs of GIAMT2D are used to validate the research hypotheses developed on the basis of existing analytical theories and satisfactorily compare with field observations.