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Innovations Towards the Next Generation of Shallow Flow Models

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Many types of environmental and geophysical flow occur on a horizontal scale that is much larger than their vertical scale. Examples include river flows, overland flows, and granular avalanches. These flows may be described using the depth-integrated Navier-Stokes equations. *Shallow flow models*, which solve these depth-integrated equations, are widely used for both research and practical applications, including understanding catchment hydrology and predicting hydrological hazards such as flooding.

The last two decades saw great advances in developing robust shallow flow models for real world applications. Robust numerical schemes have been developed to handle wet/dry interfaces, stiff source terms, and equilibrium solutions in real world applications. However, there are still challenges that are prevailing, such as insufficient computational efficiency and difficulty of solving coupled physics, which have limited current applications to either small-domain, coarse resolution, or single-process problems.

These challenges are particularly relevant with hazards brought by extreme weather events such as flooding. To better understand and predict the impacts of extreme weather events, models need to operate in much larger domains (e.g., cities or catchments) with much finer resolutions (e.g.. resolving buildings) and solve equations with coupled physics. As the magnitude and frequency of extreme weather events rapidly increase due to climate change, a new generation of shallow flow models providing such capabilities is urgently needed.

Advances in Water Resources is a key publication venue of research at the frontier of shallow flow model development, with a broad readership among scientists and engineers.This special issue of *Advances in Water Resources* is an outcome of a collection of research efforts initiated in the session *Development and application of the next generation of shallow flow models* organised as part of the 13th International Conference on Hydroinformatics, held in Palermo, Italy on July 1–6, 2018. During the preparation of the special issue, submissions from the broad research community were encouraged to represent the state of the research and highlight future challenges as well as limitations.

We collected 17 papers, which address three interwoven research challenges: (1) traditional challenges in robustly handling complex domain topography, wet/dry interfaces, and stiff source terms, especially for high-order schemes (2) improvement of computational efficiency by using high-performance computing or multiscale modelling for large-scale applications, and (3) the need to develop rigorous numerical methods to simulate equations with coupled physics to better capture the process dynamics. .

High-order numerical schemes, particularly the discontinuous Galerkin (DG) scheme, is gaining acceptance in the shallow flow research community because they can potentially significantly reduce simulation time by increasing the grid cell size. In addition, the DG scheme achieves high-order accuracy using small and local stencils, which allows for a more efficient parallelisation. However, the DG scheme discretisation introduces additional degrees of freedom to obtain this high-order accuracy, which is usually computationally costly. Faghih-Naini *et al.* (2020) increase the computational efficiency via a novel quadrature-free DG scheme on block-structured triangular meshes. Another approach for increasing the computational efficiency is the use of adaptive mesh refinement (AMR). Kesserwani *et al.* (2020) and Kesserwani & Sharifian (2020) present a multiwavelet-based AMR strategy, which in combination with a DG scheme yields a robust and efficient shallow flow model. The multiwavelet-based AMR strategy for DG schemes is also explored in (Caviedes-Voullieme *et al.*, 2020) in field-scale application cases. The multiwavelet-based AMR makes the DG scheme a competitive alternative to the more established second-order finite volume schemes. While second-order accuracy is usually considered to be sufficiently accurate, some applications require even higher order accuracy. Navas-Montilla & Juez (2020) use a high-order WENO-ADER scheme to capture turbulent structures in a channel. Without the high-order accuracy, the numerical diffusion will smear out steep gradients and hence the small turbulent eddies.

The challenge of the high computational cost of shallow flow models can also be addressed by using GPUs to accelerate the computation. Dazzi *et al.* (2020) present a GPU-accelerated shallow flow model with internal boundary conditions to represent urban structures such as bridges. Echeverribar *et al.* (2020) and Xia *et al.* (2020) use GPU-accelerated shallow flow models for flood inundation modelling at the catchment scale.

Many physical issues consist of more than one scale in them, and thus they can be approached by means of multiscale modelling approaches to increase computational efficiency. A classical multiscale method is AMR (Kesserwani *et al.*, 2020, Kesserwani & Sharifian, 2020, Caviedes-Voullieme *et al.*, 2020), but other approaches, for example subgrid-based methods, do exist. For example, Dazzi *et al.* (2020) use internal boundaries to account for subgrid-scale urban features. Li & Hodges (2020) use an artificial porosity approach to account for subgrid-scale structures in narrow channels. The artificial porosity approach is also considered by Ferrari *et al.*, (2020), who present a Riemann solver for the porous shallow flow equations. A mathematically analogy to the one-dimensional porous shallow flow equations is the Riemann problem with the shallow flow across a width discontinuity. Valiani & Caleffi (2020) analyse the augmented shallow flow system that results from this problem and derive a Riemann solver. The Lattice-Boltzmann method results directly from a multiscale consideration of the underlying physics. While its application to shallow flow modelling is still not common, they have produced promising results in terms of computational efficiency. La Rocca *et al.* (2020) present a Lattice-Boltzmann method for shallow granular flows.

Process coupling is of great interest, as water drives many processes in both rural and urban environments. Many shallow flow models expand their capabilities to include these relevant processes to tackle specific science and engineering problems such as multi-hazard modelling. The coupling of multiple processes increases the complexity of the model and may impact the robustness of the simulation. Fernandez-Pato *et al.* (2020) present a coupled surface-subsurface flow model in a study involving morphodynamics. The interface between surface and subsurface leads to stiff equations and morphodynamics introduces additional nonlinearity to the model solution. Gonzales-Aguirre *et al.* (2020) present a robust model for bedload sediment transport in shallow flows using a path-conservative approach. Krvavica (2020) studies the computational efficiency of first-order accurate numerical schemes for solving the two-layer shallow flow equations. Li *et al.* (2020) present a novel method to couple the one-dimensional and two-dimensional pipe flow to simulate flow at drainage junctions.

A potentially significant direction for future research can be found in (Shaw *et al.*, 2020), which derives wavelet-based stochastic approaches to model uncertainty. Instead of using conventional Monte Carlo methods to run simulations many times, the new method solves the equations only once and uses the probability distributions as variables. This method has the potential to enable much more efficient uncertainty quantification in various important applications such as probabilistic flood forecasting and risk management.

The collection of papers give an overview of the current research towards *the next generation shallow flow models*. With the advances of computing technologies and numerical methods, shallow flow models will move into uncharted waters, such as catchment scale hydrological dynamics and city scale flood routing. The emerging capabilities will enable us to better understand and model the more detailed hydrodynamic processes at much larger scales and contribute to addressing pressing societal needs such as resilience to hydrological hazards in the face of climate change, increasing urbanisation, population growth, and economical development.

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