Rapid Simulations of Large Scale Flood Inundations Using Porosity Functions

Vita Ayoub, Carole Delenne, Pascal Finaud-Guyot, David Mason, Marco Chini, Patrick Matgen, Ramona-Maria Pelich, Renaud Hostache

Ayoub et al. 2022, Advances in hydroinformatics, https://doi.org/10.1007/978-981-19-1600-7_4

RAPID SIMULATIONS OF LARGE SCALE FLOOD INUNDATIONS USING POROSITY FUNCTIONS

Vita Ayoub
Luxembourg Institute of Science and Technology, Environmental Research and Innovation Department, Esch-sur-Alzette, Luxembourg; HSM, Univ. Montpellier, CNRS, IRD, Montpellier, France; Inria, Team Lemon, Montpellier, France
vita.ayoub@list.lu

Carole Delenne, Pascal Finaud-Guyot
HSM, Univ. Montpellier, CNRS, IRD, Montpellier, France; Inria, Team Lemon, Montpellier, France
carole.delenne@umontpellier.fr, pascal.finaud-guyot@umontpellier.fr

David Mason
University of Reading, Department of Geography and Environmental Science, Reading, United Kingdom
d.c.mason@reading.ac.uk

Marco Chini, Patrick Matgen, Ramona-Maria Pelich, Renaud Hostache
Luxembourg Institute of Science and Technology, Environmental Research and Innovation Department, Esch-sur-Alzette, Luxembourg
marco.chini@list.lu , patrick.matgen@list.lu, ramona.pelich@list.lu, renaud.hostache@list.lu

ABSTRACT

With floods becoming more severe and frequent due to climate change and growing urbanisation, there is a crucial need to improve flood management systems. Flood hazard assessment using hydrodynamic models is more challenging at a large scale, because discretizing an area using a fine mesh is essential for obtaining accurate results, but is found to be highly expensive computationally. The emergence of sub grid models in the past few decades has enabled faster simulations by using coarser cells while preserving small-scale topography variations within one cell. In this context, we propose a modelling framework based on the shallow water 2D model with depth-dependant porosity (SW2D-DDP). We evaluate this approach by setting up a standard 2D shallow water model (SW2D) considered as a benchmark. The 2007 flood event of the River Severn is used as a test case. Our preliminary results demonstrate a high accuracy (~90% during flood peak) and a low computational cost with a ~350 runtime reduction factor of the proposed model compared to a standard model. This opens up new perspectives for large scale applications over areas where bathymetric data is not available.

1. INTRODUCTION

Well-conducted flood risk assessments are key for decision making related to flood mitigation, preparedness and response. In order to better anticipate and further reduce potential flood risks in flood-prone areas, there is a crucial need for constantly improving our flood management systems [1, 2]. In this context, the most commonly used flood inundation (hydraulic) models are based on the Shallow Water Equations (SWE), which can be solved in one (1D) or two dimensions (2D). While 1D models are relatively easy to set up and fast to run [3], their neglect momentum transfers between the channel and the floodplain leads to inaccurate predictions of overbanking flow and in presence of complex topographies. In 2D flood models, the accurate representation of topography requires a fine discretization of the area of interest (including main channel and floodplains). Consequently, the main limitation of accurate modelling of large-scale floods is associated with a very expensive computational cost.

Sub-grid modelling approaches have tackled this challenge and gained a growing interest as they are a good compromise between accuracy and high computational efficiency. Indeed, they enable faster simulations as they use coarser computation cells while accounting for small-scale topography variations within the cells. Including the porosity concept as a way to upscale the shallow water equations has become more popular in the past twenty years. Porosity is defined as the fraction of a computational cell/edge available to the flow, depending on water elevation. In this context, the aim of this study is to develop a modelling framework based on the Shallow Water 2D - Depth Dependant Porosity (SW2D-DDP) [4] model, and to evaluate its ability for rapid flood inundation simulations at the river scale. To carefully evaluate the proposed modelling framework, we compare the SW2D-DDP simulation result with a standard 2D shallow water model result. Benchmarking the porosity model against a high-resolution 2D model enables the evaluation of our approach across space and time. It also helps to explore strengths and limitations of the proposed approach in comparison with state-of-the-art approaches. Our study site is a 1,500 km^2 floodplain that has frequently experienced flooding in the last decades, and is located at the confluence of the Severn and Avon Rivers in the United Kingdom. The 2007 flood event of the Severn River is used as a test case.

The remainder of this paper is organised as follows. In section 2, the proposed modelling framework and the standard approach used for its evaluation are introduced. Next in section 3, the study site, available data, and model set up are described. In section 4, the preliminary results are presented. In section 5 we conclude with the main outcomes of the study.

2. METHOD

In this section, we describe the proposed modelling approach based on the SW2D-DDP model. To evaluate this framework, we set up a standard 2D shallow water model (SW2D) as a benchmark. The SW2D solves the shallow water equations (SWE) on structured or unstructured grids using a finite volume scheme. The bottom elevation inside a computational cell has a unique value, equal to the average elevation of the cell's nodes. Structures such as roads or drains, and streams should be intrinsically represented via cells smaller than their dimensions, which increases the overall number of computational cells in the SW2D model mesh. In order to represent flow in the riverbed, 6 cells are considered in the width of the river while maintaining the cell’s length at maximum twice its width to avoid model instabilities (**fig. 1** left).

The Shallow Water 2D with Depth Dependant Porosity (SW2D-DDP) model [5] solves the upscaled SWE; using the porosity concept, small-scale obstacles affecting the flow are taken into consideration, without the need to detail their geometry in the mesh. This allows using coarse instead of fine grid cells. Inside each cell, a bottom elevation field z_b is provided via a porosity distribution function varying with the water depth. Two types of porosities are distinguished: a storage porosity inside a cell and a connective porosity on the edges of a cell. They represent the amount of water that can be stored/transferred per unit domain and boundary for a unit variation in the free surface elevation z_s assuming it is known. The river channel flow is represented with cells defined larger than the river width (**fig. 1** right).

Small-scale topography is taken into account via porosity laws. In our proposed approach we use law types 0 and 3: 1) law type 0 allows to handle porosities in the floodplains, where the distribution of ground elevations inside each cell are first retrieved from the Digital Elevation Model (DEM), then discretised using a piecewise constant functions of N segments with "equidistant" porosity values associated to elevation values; 2) law type 3 handles porosities in the riverbed with a simplified trapezoidal shape assumption.

The parameter retrieval of the porosity law in each cell and edge is carried out automatically using the available DEM and bathymetric information. First, storage porosities are computed. Then, the porosity law type used for the edges is selected depending on the location of their adjacent cells: law type 3 is used inside the riverbed (cross sections, i.e., edges between two cells of type 3) and law type 0 is used in the floodplain (between two cells of type 0) and on riverbanks (between a riverbed and a floodplain cells). To accurately represent overbank flows, the nodes of the riverbed cells are positioned on the dikes in both models. Due to numerical constraints detailed in [4], the edge porosity has to be maintained smaller than the cell porosity for any elevation. The edge porosity values are thus computed so as to ensure that the aforementioned condition is respected.

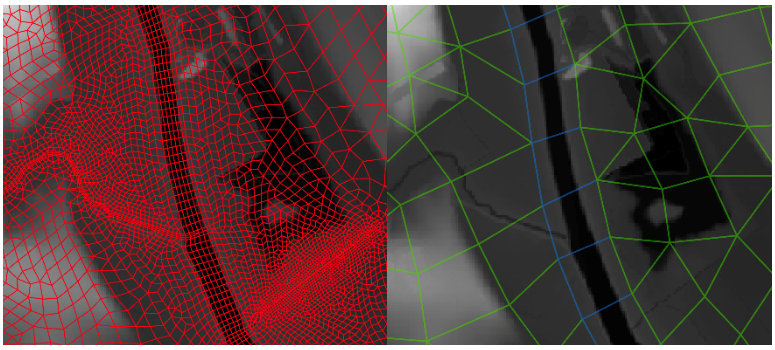

Fig. 1: 1km^2 subset of the standard model mesh (left) and the porosity model mesh (right). The blue cells are riverbed cells with porosity law type 3.

3. STUDY SITE, AVAILABLE DATA AND MODEL SETUP

The study site is located at the confluence of the Severn and Avon Rivers around the city of Tewkesbury and has been subject to frequent flooding due to intense precipitation. **Fig.** 2 shows the area of interest of around 1500 km^2 and the river network along with the available gauging stations. Topographic data is provided by a 2m resolution LiDAR DEM, with a vertical accuracy of 10cm. Bathymetric data is reconstructed using three river cross section measurements at the upstream and downstream boundaries of the model. A simplified trapezoidal shape assumption is used to represent the riverbed. The July 2007 flood event is considered as a test case to evaluate the proposed modelling approach. Hydrometric data at available gauging stations is given by the UK Environmental Agency (EA).

Fig. 2: Study site map showing the river network and the location of the gauging stations.

Discharge time series are imposed as upstream boundary conditions of the hydraulic model (Severn at Saxons Lode and Avon at Bredon). Water level time series are used as downstream boundary condition at Deerhurst (**fig. 2**). The initial condition is a fixed water level equal to the downstream condition. A uniform Strickler coefficient K_s = 50 m$^{1/3}$s^{-1} is used for the river course. The duration of the 2007 flood event simulation is 17 days (18 July - 04 August).

4. PRELIMINARY RESULTS

The SW2D-DDP model results are evaluated using the SW2D model as a benchmark. **Fig. 3** shows the Critical Success Index (CSI) and Overall Accuracy (OA) time series computed on a daily frequency for evaluating the SW2D-DDP simulated flood maps using the SW2D simulated flood maps as reference. A very good agreement between the two models (accuracy of 95%) is observed during the flood peak. Performance metrics are slightly lower in the rising limb, and decrease more in the falling limb. This implies that the fill and drain dynamic in the SW2D-DDP model is different from that in the SW2D model.

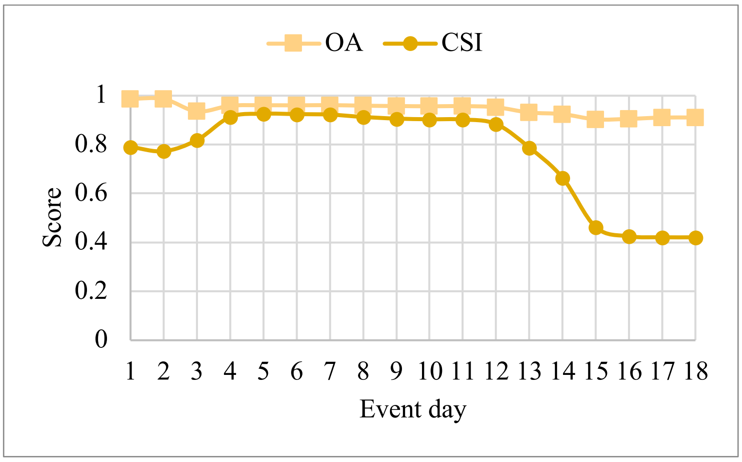

Fig. 3: CSI and OA scores time series showing agreement between simulated (porosity) and "reference" (standard) flood extent maps, CSI: Critical Success Index & OA: Overall Accuracy.

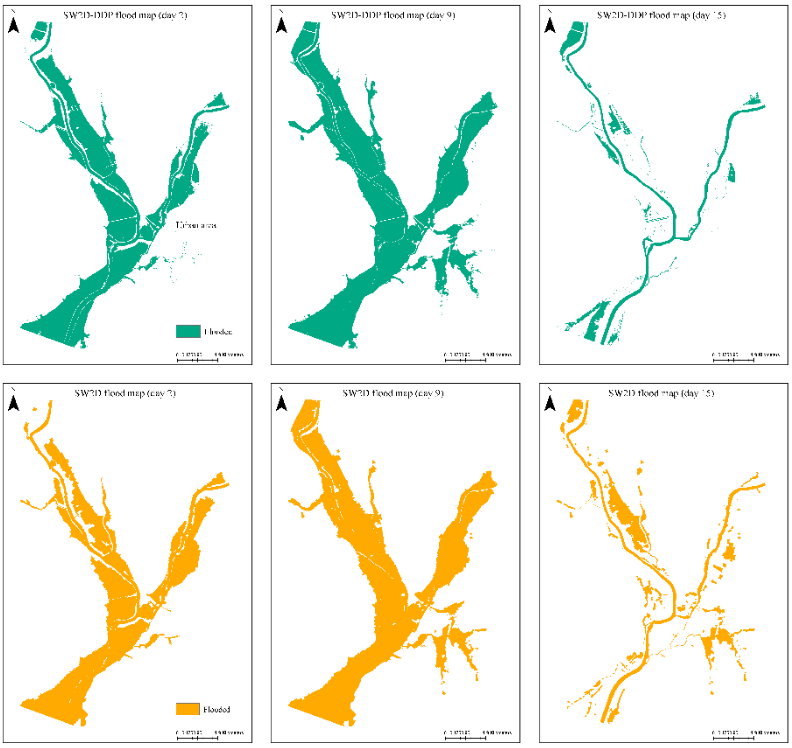

Fig.4: Flood maps simulated by the porosity-based (green) and standard (orange) models on days 2, 9 and 15 of the 2007 flood event.

Fig. 4 show a series of flood extent maps simulated by the SW2D-DDP (green) and SW2D (orange) models. During the rising limb (**fig.4** left), the porosity-based model exhibits a good agreement with the standard model, while locally inundating slightly larger areas especially in the upstream part as well as in little drains in the urban area, at the Severn-Avon confluence (see box in **fig.** 4). This indicates the SW2D-DDP induces overbanking earlier than SW2D. Oppositely, a smaller inundation extent is visible locally nearby the Avon River. During the flood peak (**fig.4** center), the similarity between both maps is very high. **A** substantially smaller flood extent simulated by SW2D-DDP is observed during the falling limb (**fig. 4** right). This indicates that almost all floodplain water comes back to the stream in the SW2D-DDP simulation while a substantial volume of water remains present in the floodplain in the SW2D simulation. This effect is dominant in the eastern Severn floodplain and around the urban settlements. Overall, the observed dynamic suggests that the porosity-based model fills in and drains floodplain water faster than the standard model.

5. CONCLUSIONS

In this paper, we propose a modelling framework based on a shallow water model using the porosity concept (SW2D-DDP) in order to evaluate its ability to rapidly simulate flood inundations. Using the depth-dependant porosity enables representing small-scale topography without the need to detail the mesh geometry. Simulating a real flood event over a 1500 km^2 area around the Severn and Avon confluence, and comparing the simulation results for both models, we draw the following conclusions:

- The proposed modelling approach enables to simulate flood extent maps very similar to the ones simulated by the standard SW2D model with 90% agreement.
- The SW2D model mesh is composed of 29,772 cells while the SW2D-DDP model mesh contains only 1,042 cells, which implies the mesh discretization is easier and faster in the proposed framework.
- The SW2D-DDP model simulation is c.a. 350 times faster than that of the SW2D model, thereby substantially reducing computational costs, due to the significant decrease of the number of computational cells.

Overall, this study shows the SW2D-DDP model holds a good potential for large scale flood modelling. The results are at a satisfying performance level and at lower computational costs. Future works will be devoted to other configurations where we simulate other real test cases and evaluate the proposed modelling framework using observation data as well as in situ measurements.

ACKNOWLEDGEMENTS

This study was funded by the National Research Fund of Luxembourg through the CASCADE project (Grant no. C17/SR/11682050).
The hydrometric data is provided by the UK environment agency.

REFERENCES AND CITATIONS

[1] Biswajeet Pradhan, Ulrike Hagemann, Mahyat Shafapour Tehrany, and Nikolas Prechtel. An easy to use arcmap based texture analysis program for extraction of flooded areas from terrasar-x satellite image. Computers & geosciences, 63:34–43, 2014.

[2] Mahyat Shafapour Tehrany, Biswajeet Pradhan, and Mustafa Neamah Jebur. Flood susceptibility mapping using a novel ensemble weights-of-evidence and support vector machine models in gis. Journal of hydrology, 512:332–343, 2014.

[3] Jean Cunge. Practical aspects of computational river hydraulics. Pitman Publishing Ltd. London,(17 CUN), 1980, 420, 1980.

[4] V. Guinot, C. Delenne, A. Rousseau, and O. Boutron. Flux closures and source term models for shallow water models with depth-dependent integral porosity. Advances in Water Resources, 109:133–157, 2018.

[5] Inria Lemon Team. SW2D Software: http://sw2d.inria.fr/.