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Catchment-scale high-resolution flash flood simulation using the GPU-based technology

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Abstract

A number of studies have predicted more frequent and intensive storms as a result of climate change in UK and other parts of the world, which may consequently cause more hazardous flash floods in steep catchments of small to medium size (e.g. up to 100km²). These flash floods are commonly characterized by high-velocity overland flow as a result of rapid catchment response to the intense rainfall. The hydrological processes related to the rapid catchment response are poorly understood and reliable prediction is generally beyond the capability of traditional hydrological models or simplified hydrodynamic models. This work aims to present a shock-capturing hydrodynamic modelling system to simulate the complex rainfall-runoff and the subsequent flash surface flooding process in a rapid-response catchment. The model solves the fully 2D shallow water equations using a finite volume Godunov-type shock-capturing numerical scheme for the rapidly varying overland flow hydrodynamics following intense rainfall. Typically, this type of shock-capturing hydrodynamic models is not able to provide efficient and high-resolution simulations for large-scale flash flood events due to their high computational demand. In order to substantially improve the computational efficiency and enable catchment-scale simulations at very high resolution involving millions of computational nodes, the model is implemented on GPUs for high-performance parallel computing. After being validated against the analytical benchmark of Tilted V-catchment test, the GPU-accelerated hydrodynamic modelling system is applied to simulate the rainfall-runoff process in the 42km² Haltwhistle Burn Catchment in England.

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1. Introduction

A number of recent studies [1] have suggested more frequent and intensive storms as a result of climate change in the UK and other parts of the world, which may consequently cause more hazardous flash floods in steep catchments of small to medium size (e.g. up to 100km²). These flash floods are commonly characterized by rapid-varying overland flow as a result of complex and rapid catchment response to intense rainfall. Traditionally, hydrological models or simplified hydrodynamic models have been used to predict these events at a catchment scale. However, most of these simplified models are not capable of depicting the rapid catchment responses and complex surface flow processes to predict accurate depths and velocities; their reduced representation of physical complexity may lead to increased sensitivity to and dependence on parameterization [2].

Hydrodynamic models based on the solution to the shallow water equations are able to more accurately simulate the dynamics of overland flows. These models are much less dependent on parameterization and thus provide more reliable predictions of the rainfall-runoff processes and the resulting surface flooding. These models also provide effective tools to better understand the hydrological processes associated with intense rainfall. However, these full hydrodynamic models are generally computationally very demanding and therefore can only be applied to perform simulations for short-duration events at localized scale; attempts have also been made to run simulations over catchment scales at coarse resolutions, which inevitably compromises the benefit of using hydrodynamic models (e.g. [3], [4]). In the last few years, due to its unprecedented computational power, graphic processing units (GPUs) have been applied in many fields of scientific computing to improve model performance for wider applications, including the application to solve the shallow water equations (e.g. [2], [5], [6]). Harnessing the advantages of GPUs, high-resolution hydrodynamic simulation of large-scale shallow flow problems has become feasible. For example, Liang and Smith [7] have applied the GPU-accelerated High-Performance Integrated hydrodynamic Modelling System (HiPIMS) to predict an idealized urban flood event in part of Glasgow and a hypothetical fluvial flood due to defense failure at Thamesmead at very high resolutions.

In this work, HiPIMS is further developed and applied to simulate the rainfall-runoff process at catchment scales. After being tested for an idealized case with analytical solution, the model is then used to simulate the hypothetical rainfall-runoff-flooding processes in the 42km² Haltwhistle Burn Catchment in England, demonstrating HiPIMS's capability. Simulations on different grid resolutions are run to demonstrate the sensitivity of results. The rest of the paper is organized as follows: In section 2, the governing equations and numerical scheme are briefly reviewed; in section 3, the model is firstly validated against the analytical tilted V-catchment test and then applied to predict a hypothetical flood event at the Haltwhistle Burn Catchment; finally brief conclusions are drawn in section 4.

2. GPU-based hydrodynamic model

Hi-PIMS solves the fully 2D shallow water equations given as follows

$$\frac{\partial \mathbf{q}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} = \mathbf{s} \quad (1)$$

$$\mathbf{q} = \begin{bmatrix} \eta \\ hu \\ hv \end{bmatrix}, \quad \mathbf{f} = \begin{bmatrix} hu \\ hu^2 + \frac{1}{2}g(\eta^2 - 2\eta z_b) \\ huv \end{bmatrix} \quad (2)$$

$$\mathbf{g} = \begin{bmatrix} hu \\ huv \\ hv^2 + \frac{1}{2}g(\eta^2 - 2\eta z_b) \end{bmatrix}, \quad \mathbf{s} = \begin{bmatrix} s_r + s_i \\ -\frac{\tau_{bx}}{\rho} - \frac{g\eta\partial z_b}{\partial x} \\ -\frac{\tau_{by}}{\rho} - \frac{g\eta\partial z_b}{\partial y} \end{bmatrix}$$

where η is the surface elevation (i.e. water level), h is the water depth, u and v are the depth-averaged velocities along the x and y -direction, z_b is the bed elevation, s_r and s_i are the source and sink terms due to rainfall and

infiltration, g is the gravitational acceleration, ρ is the water density, τ_{bx} and τ_{by} are the bed friction stresses calculated using the Manning equation

$$\tau_{bx} = \rho C_f u \sqrt{u^2 + v^2}, \tau_{by} = \rho C_f v \sqrt{u^2 + v^2} \tag{3}$$

where $C_f = g n^2 / h^{1/3}$ is the bed roughness coefficient with n being the Manning coefficient.

In order to capture the complex flow dynamics, a finite-volume Godunov-type shock-capturing scheme is adopted to solve numerically the above governing equations on uniform Cartesian grids. A two-step unsplit MUSCL-Hancock method is implemented to achieve second-order numerical accuracy in both space and time. In the predictor step, intermediate flow variables are calculated to half of a time step $\Delta t/2$ using the following formula

$$\mathbf{q}_i^{k+1/2} = \mathbf{q}_i^k - \frac{\Delta t}{2\Delta x}(\mathbf{f}_E - \mathbf{f}_W) - \frac{\Delta t}{2\Delta y}(\mathbf{g}_N - \mathbf{g}_S) + \frac{\Delta t}{2} \mathbf{s}_i^k \tag{4}$$

where the superscript k denotes the time level; i is the cell index; subscript E, W, N and S indicate the east, west, north and south cell interfaces of cell i ; Δt is the time step; Δx and Δy are the cell size in the x and y -direction. The fluxes vectors $\mathbf{f}_E, \mathbf{f}_W, \mathbf{g}_N$ and \mathbf{g}_S are calculated directly from the reconstructed face values of the flow variables at the middle point of the cell interface under consideration; the MUSCL slope limited linear reconstruction based on cell-center values of the flow variables is used to obtain these face values. The minmod slope limiter is used in this work to prevent any spurious oscillations in the numerical solution and guarantee better numerical stability.

In the corrector step, the flow variables are updated to a new time step using the following time-marching formula

$$\mathbf{q}_i^{k+1} = \mathbf{q}_i^k - \frac{\Delta t}{\Delta x}(\mathbf{f}_E - \mathbf{f}_W) - \frac{\Delta t}{\Delta y}(\mathbf{g}_N - \mathbf{g}_S) + \Delta t \mathbf{s}_i^{k+1/2} \tag{5}$$

where the interface fluxes $\mathbf{f}_E, \mathbf{f}_W, \mathbf{g}_N$ and \mathbf{g}_S are calculated using an HLLC approximate Riemann solver.

In the above finite volume Godunov-type numerical scheme, a local bed modification technique is further applied to ensure non-negative water depth and maintain the C -property during a simulation. The slope source terms are estimated directly using central differences. The friction source terms are discretized using a point wise semi-implicit scheme to avoid unrealistic flow velocity when the water depth becomes small. The rainfall rate s_r is provided by design rainfall intensity or field measurements. The infiltration rate s_i is determined using the popular Green-Ampt approximation. More details of the numerical scheme may be found in Liang [8].

In order to substantially improve the computational efficiency of the model for large-scale applications, the model is developed using the open source computing language OpenCL to support simulations on modern computing hardware devices, including GPUs and CPUs. More details of the OpenCL implementation can be found in Smith and Liang [2]. The GPU accelerated HiPIMS can be up to 40 times computationally more efficient than its counterpart running on a single CPU core.

3. Results

In this section, the capability of HiPIMS to represent rainfall-runoff process is demonstrated by firstly considering an idealized case in a V-shape catchment and then predicting a hypothetic surface flood event induced by intense rainfall in the Haltwhistle Burn Catchment, England. The CFL number is set to 0.5 for all of the simulations.

3.1 V-shape idealized catchment

This test case aims to verify the accuracy of a model in simulating the shallow overland flow following a uniform

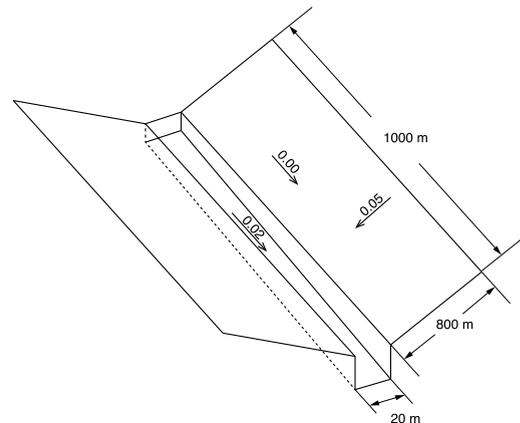


Figure 1. Geometry of the V-shaped channel (reproduced from Simons et al. [11]).

rainfall event. The approximated kinematic solutions in terms of the hydrographs are derived by Overton and Brakensiek [9], assuming steady and uniform rainfall over an impermeable V-shaped idealized catchment with a geometry as shown in Figure 1. The slopes/ gradients of the hillsides and the channel are 0.05 and 0.02, respectively. The Manning coefficient is set to be $0.015 \text{ s/m}^{1/3}$ for the hillsides and $0.15 \text{ s/m}^{1/3}$ for the channel. The simulation is done at a 10 m resolution and lasts for 12000 s. Constant rainfall is imposed for 5400 s, with an intensity of 10.8 mm/h.

The predicted hydrographs on the hillside and at the channel outlet are compared with the analytical solutions in Figure 2. The numerical results agree satisfactory with the analytical solutions, confirming that capability of the model in simulating the overland flow and representing rainfall-runoff process. It should be noted that there is no analytical solution for the descending leg of the channel outlet hydrograph.

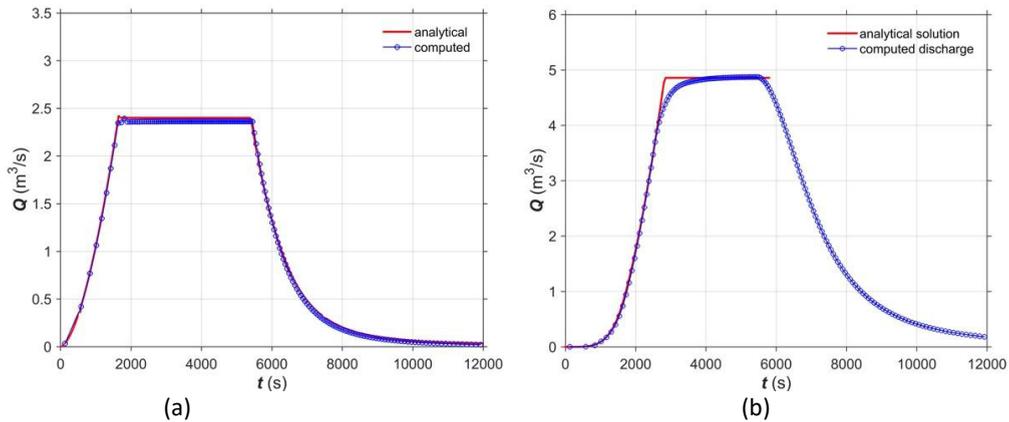


Figure 2. Predicted and analytical hydrographs: (a) hillside; (b) channel outlet.

3.2 Flash flooding in the Haltwhistle Burn Catchment, England

The Haltwhistle Burn catchment, with an area of about 42 km^2 , is a small catchment in Northumberland, England. It is one of the Rapid Response Catchments recognised by the Environment Agency. Further introduction of the catchment may be found in the website of Haltwhistle Burn ‘Community-based Catchment Management’ project [10]. The topography of the catchment is shown in Figure 3.

In order to demonstrate the model’s capability to simulate fast catchment response, a hypothetical flood event is simulated, with the rainfall intensity provided in Figure 4(a). Two simulations are performed with different spatial resolutions, i.e. 5m and 10m. For the simulation with a 5m resolution, 5 million computational cells have been created in the rectangular domain embracing the catchment. The Manning coefficient is set to be 0.03 throughout the whole domain. The catchment is assumed to be wet and infiltration is negligible. The simulations are carried out for the entire 12-hour event. During the simulations, water level is monitored at six gauges, with three of them (Gauge 1-3) located at upstream small streams and another three located in the Haltwhistle Burn River.

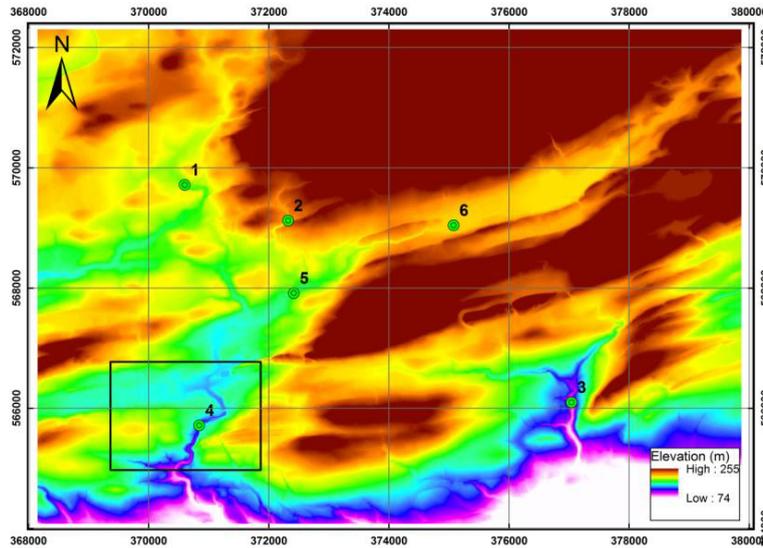


Figure 3. Haltwhistle Burn catchment and locations of six water level gauges.

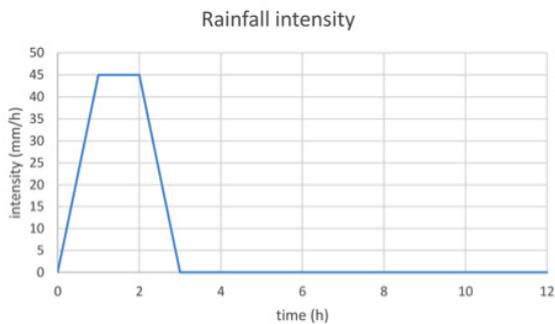


Figure 4 Hypothetic rainfall event.

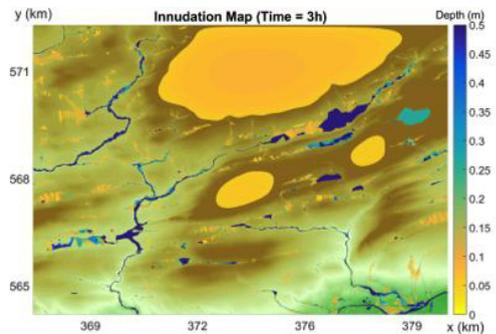


Figure 5 Inundation map after 3 hours.

Figure 5 presents the inundation map at $t = 3h$ when the rain stops. Surface water has mostly been drained to the streams and low-lying areas. Figure 6 presents the inundation maps at different output times for a localized area at the downstream of the river (the area inside the small square in Figure 3). As observed from the results, the catchment starts to respond to the rainfall after it starts. Although it is not obvious, inundation starts to occur at $t = 1h$; a significant area has been inundated at $t = 3h$; after reaching its maximum extent, the flood starts to retreat as it can be observed for $t = 5h$ and $7h$. This essentially represents the surface flow process following an intense rainfall event.

In order to show the sensibility of the simulation results to spatial resolutions, a further simulation is run at a spatial resolution of 10m and time histories of water level are compared at the six flow gauges in Figure 7, with the locations of the flow gauges indicated in Figure 3. From the results, the flood level is found to be sensitive to spatial resolution of the model. Correct prediction of the water level at Gauge 4 is considered to be the most important as it is directly upstream of the Haltwhistle town, which will provide essential information for flood warning and any flood mitigation scheme. At this gauge, the peak water level predicted by the simulation with 5m resolution is almost 1m higher compared with that obtained with a 10m resolution. At the upstream Gauge 1, the flooding processes predicted by the two spatial resolutions are different, with the coarse-grid simulation predicting a much higher peak. The results indicate that hydrodynamic simulation of the catchment-scale rainfall-runoff process is sensitive to the spatial resolutions. Higher spatial resolution may be needed in order to correctly represent the small-scale topographic features and captures the transient surface flow process. This poses a great challenge to the

traditional CPU-based hydrodynamic models due to their high computational demand.

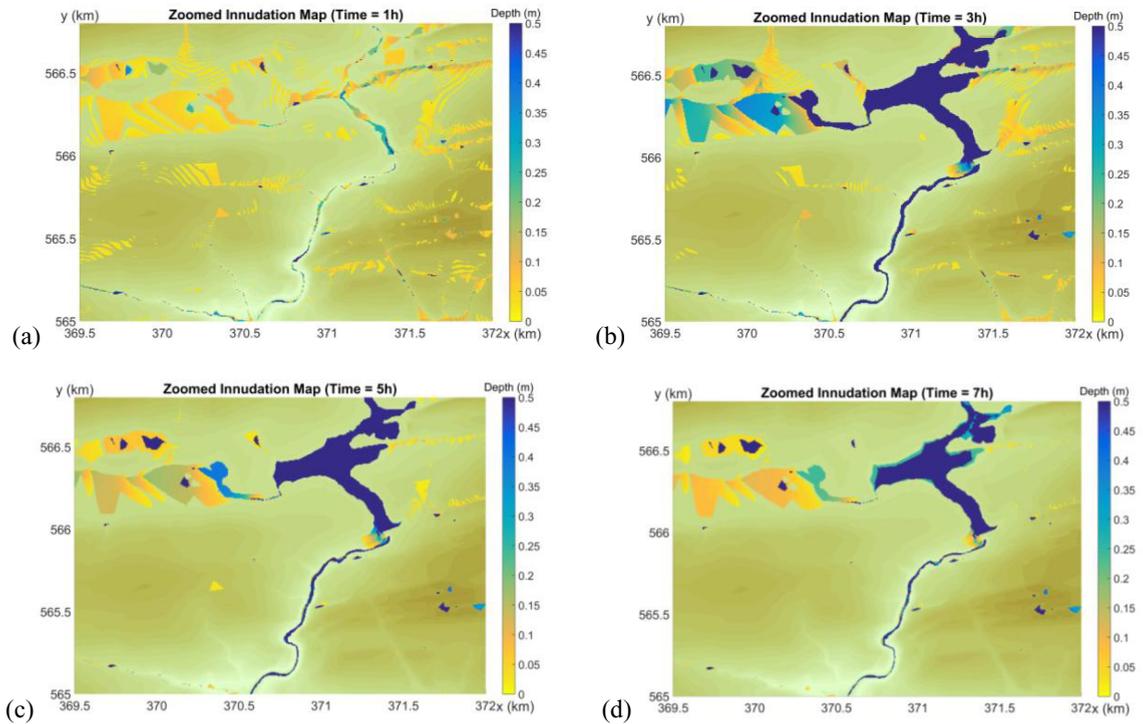


Figure 6. Zoom-in inundation maps at different output times: (a) $t = 1h$; (b) $t = 3h$; (c) $t = 5h$; (d) $t = 7h$.

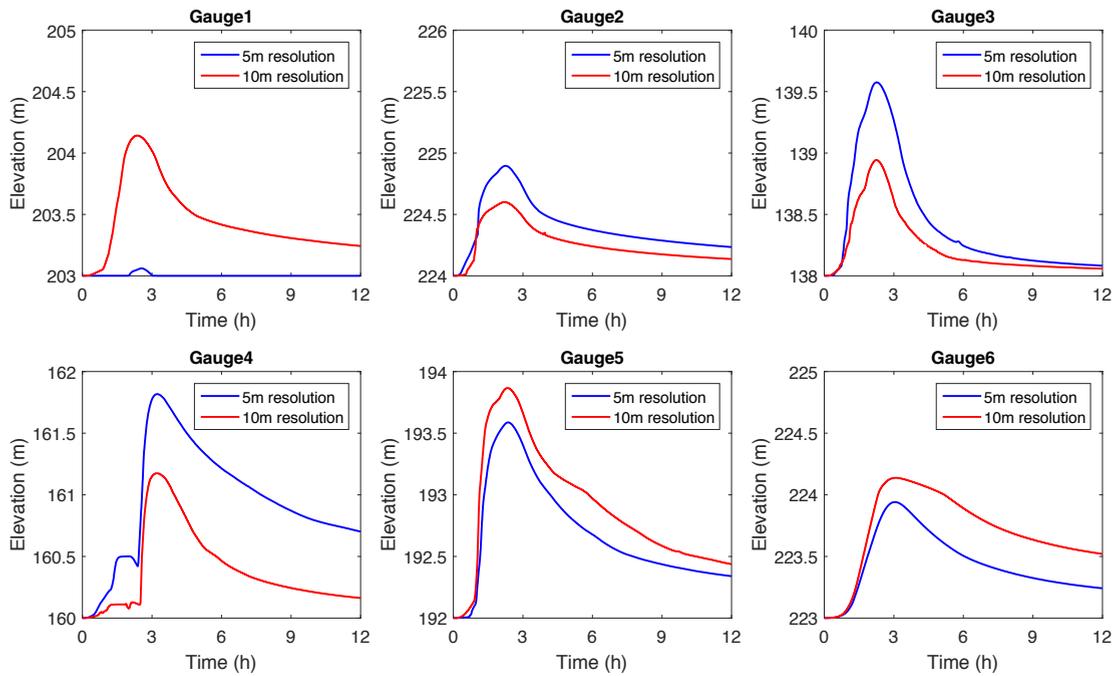


Figure 7 Time histories of water level at the six flow gauges as shown in Figure 3.

With regard to the performance the current GPU-accelerated hydrodynamic model, the simulation of the 12-hour flood event involves 2.5h of runtime on a single Tesla K80 GPU, which involves 5 million computational nodes at the 5m resolution. This simulation is nearly 5 times faster than real time, confirming the capability of HiPIMS for large-scale high-resolution simulation of rainfall-runoff-flooding processes.

4. Conclusions

In this work, we have presented a GPU-accelerated shock-capturing hydrodynamic model for simulating catchment-scale rainfall-runoff and flooding processes at high resolutions. The model has been firstly validated against an idealized test of rainfall-runoff over a V-shape catchment. The numerical predictions agree closely with the analytical solutions, demonstrating the capability of the model in predicting rainfall-runoff induced overland flows. The model is then applied to simulate a flood event in the Haltwhistle Burn catchment, England driven by hypothetical rainfall. Two simulations with different resolutions are performed and significant discrepancies are observed between the simulation results. This indicates that hydrodynamic simulation of rainfall-runoff process is sensitive to spatial resolution at a catchment scale. More reliable simulation results may be obtained only with adequate representation of small-scale topographic features in the catchment.

To complete 12-hour Haltwhistle flood simulation at 5m resolution with 5 million computational nodes, HiPIMS only requires 2.5 hours of runtime, i.e. the simulation is nearly 5 times faster than real time. This confirms the much improved performance of the current GPU-accelerated model in comparison with a similar CPU-based model. With its superior computational efficiency, HiPIMS is able to support high-resolution simulations at a large scale and hence provide a new-generation of modelling tools for understanding the highly transient hydrological processes induced by intense rainfall.

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