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A NEW TWO-DIMENSIONAL CELLULAR AUTOMATA APPROACH FOR FAST URBAN FLOOD INUNDATION MODELLING

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There have been significant increases in frequency and severity of flood events in major cities across the world causing a considerable loss of life and property. It is highly likely that the risk of flooding will be exacerbated by the potential impact of climate change resulting in more frequent extreme rainfall events. A fast flood inundation model could provide invaluable information for flood risk analysis. Predictions made based on 1D model provide limited information about the flow dynamics whereas 2D models based on the solution of conventional partial differential equations require substantial computational time and cost limiting their use on small scale projects. In this work an alternative approach called cellular automata (CA), is formulated and employed to simulate pluvial flood inundation events. In this approach, the state (e.g., water level) of an individual cell is repeatedly updated in discrete time steps according to simple local rules depending upon the states of neighbour cells and the cell itself. This state updating algorithm contributes to a great reduction in computational cost that is otherwise incurred when solving conventional partial differential equations. This paper presents an application of the proposed CA model to an urban area in the UK to assess its performance. The proposed CA approach uses readily available high resolution Geographical Information System (GIS) data such as those obtained by the Light Detection And Ranging (LiDAR) technique. In the study, the square grid digital elevation model provides itself a discrete space for the CA setup and local rules are operated in the von Neumann type neighbourhood to simulate the spatio-temporal evolution of pluvial flooding. The results from the CA model are compared with those of a physically based 2D urban inundation model, and are found to be in good agreement.

INTRODUCTION

Flood inundation models based on conventional full-dynamic partial differential equations take considerable computational time and resources. The popular trend is to reduce the full dynamic model into its simplified derivatives so as to meet the specific computational capabilities. Urban flood inundation modelling involves computational techniques to simulate spatial and temporal evolution of water flow into a wide surface area consisting of many complex features. These mainly involve numerical solutions of physically based flow governing equations. Data-driven empirical stochastic models which employ probabilistic approaches to predict flood extent are also used [1]. It has always been a challenging task to model urban flood speedily and accurately because of the scale and complexity involved in the urban setup. The state of the art in urban flood modelling is a coupled 1D/2D (sewer/overland) flow model also known as the dual-drainage approach [2]. Many investigations have been carried out to develop models which allow linking of complex physical processes involved in urban flooding. A non-inertial urban inundation model (UIM) developed by Chen et al. [3] couples surface (2D) and subsurface (1D) sewer flows by taking into account the bidirectional flows through the manholes in urban area.

Various approaches have been developed to reduce the computational time of 2D surface flood models. Some attempt to divide the 2D modelling area into a series of flow paths and ponds, and then implement a 1D approach to simulate overland flow. A rapid flood model proposed by Lhomme et al. [4] divides the domain into various impact zones (IZs) consisting of accumulation points and communication points where the transfer of water takes place. The method spills and then merges IZs as the evolution of inundation proceeds. A similar model presented by Maksimović et al. [5] for urban pluvial flooding uses an automated overland flow pathway analysis in which a 1D-1D dual-drainage concept has been implemented. The automated algorithm has been employed to create a surface network of ponds and surface flow paths. However, considerable pre-processing is needed, thereby increasing the total runtime. Furthermore, 1D-2D modelling has been criticised as being too slow and difficult for efficient real-time flood forecasting [6]. Vojinović and Tutulic [6] proposed a method in which building elevations are raised and road surfaces are lowered to model urban flood. However, the method is time consuming due to the pre-processing needed, thus making the model computationally inefficient. Another approach to improve computational efficiency of 2D flood modelling is JFLOW-GPU by Lamb et al. [7] who achieved massive parallelisation using graphical processing units (GPUs) to reduce the computational time.

Applications of Cellular Automata (CA) methods in urban areas have been mostly to land use change modelling. Those models are normally stochastic and/or expert rule-based. During the last decade, however, methods for describing physically-based, deterministic systems within the CA framework have become popular [8]. Frisch et al. [9] developed the earliest hydro-dynamical CA model to solve the isotropic Navier-Stokes equation. They employed a local particle collision rule on a hexagonal discrete grid to simulate fluid flows. In some complex natural phenomena, novel parallel computing models represent a valid alternative to standard differential equation methods. In particular, CA provides such an alternative approach for some complex natural systems, whose behaviour can be described in terms of local interactions of their constituent parts [10]. Thomas and Nicholas [11] applied a CA model to simulate braided river flow by routing the flow from the cell under consideration into five downstream cells. Coulthard et. al [12] developed the CA Evolutionary Slope And River (CAESAR) model to simulate the sediment evolution along river channels. The four-sweep scanning algorithm employed for four directions in CAESAR impacts on its performance such that the model efficiency cannot be assured. A rapid inundation model as proposed by Krupka et al. [13] might be useful for flood risk management rather than for flood defence and analysis because it only calculates the final inundation extent employing a flood-storage cell algorithm. As such, the model does not allow dynamic interaction between river and flood plain flow. Krupka et al. adopted a CA-like concept in their model which used three states of a cell- dry, active and inactive, to determine the flood inundation extent. However, the model lacks the timing of inundation and dynamic spreading.

The stability criterion in storage cell models like LISFLOOD-FP [14] is such that high resolution grids require smaller time steps relative to full 2D shallow water equation models. A CA model proposed by Dottori and Todini [15] employs Manning's formula to calculate the interfacial discharges and is similar to LISFLOOD-FP which works on diffusive storage cell concept.

This work describes a reduced complexity model for urban flood inundation based on the CA approach. In this approach, the interfacial outflow discharges are calculated using simple local rules in the neighbourhood considered. The motivation for this research is the development of a fast flood inundation model so that it can be used for flood risk calculations, where a large number of model runs are needed. The proposed CA model is for pluvial flood modelling in which the spatio-temporal variations in flood depth and velocity are governed by local rules in the neighbourhood.

PROPOSED CA APPROACH

The proposed model consists of five essential features of a true cellular automaton: a discrete space, neighbourhood, cell state, discrete time step and a transition rule [16]. The square grid DEM provides the discrete space for the CA set up. The neighbourhood chosen consists of the cell itself and its four cardinal adjacent cells, called the von Neumann type neighbourhood. The effective uniform rainfall lands directly on the whole area of the terrain considered. Hydrological losses are not considered within the CA model. The movement of water is modelled as occurring from the central cell. Only the outflows from the cell under consideration are calculated based on the ranks of the cells in the neighbourhood (NH). Any inflow fluxes into the cell under consideration are calculated as outflows from other locations in the cell neighbourhood. In this way, the distribution algorithm is dynamically applied according to the differences in water surface elevations.

Local Rules

Flux calculation

The calculation process starts with cell ranking locally in the neighbourhood based on water surface elevations. For the von Neumann neighbourhood type, there will be five discrete states of cell ranks $\{r = 1, 2, 3, 4, 5\}$. Other global state variables such as depth of flow and ground elevations are continuous in nature. If the rank of the central cell is r_c, there will be r_c-1 number of cells getting water as flux through the cell boundaries in the neighbourhood considered. For a detailed description of the algorithm, readers are advised to refer to previous publication [17]. In the layer wise allocation, there will be r_c -1 layers as well to receive water, if enough volume is available. Thus outflow volumes for i^{th} layer can be given by the following recursive formula that is applied locally for each cell considered:

$$\Delta V_i = \min \left\{ A_0 d_0 - \sum_{k=1}^{i-1} \Delta V_k ,\ \frac{i}{(i+1)} \left(A_i \Delta WL_i - \sum_{k=1}^{i-1} \Delta V_k \right),\ i\left(A_i \Delta WL_i - A_{i+1} \Delta WL_{i+1}\right) \right\} \tag{1}$$

where ΔV_i is the volume of water distributed to i^{th} layer from the central cell having rank r_c, d_0 is the water depth in the central cell with Area A_0 at previous time step, A_i is the area of cell with rank i, and ΔWL_i is the difference of water surface levels between i^{th} layer and the central cell. Thus outflow flux from the central cell to the cell of rank r is calculated by

$$F_r = \sum_{k=r}^{r_c - 1} \frac{\Delta V_k}{k} \tag{2}$$

Depth calculation

A very important step in the CA approach is its state update. In this approach the global continuous state is the flow depth in a cell, which is updated for every new time step. The following transition rule is used to update the flow depth:

$$d^{m+1} = d^m + \frac{\sum F}{\Delta x \Delta y} \tag{3}$$

which makes Eq. (3) equivalent to the mass conservation equation:

$$\frac{\partial V}{\partial t} + \nabla \cdot \mathbf{Q} = S_r \tag{4}$$

where, V is the volume of water in the cell, $\mathbf{Q}$ is the flux vector at cell boundary and S_r is the source term, e.g., rainfall in this case. To control the outflows from the cell and to avoid oscillations of water depth in subsequent computation steps, non-dimensional flow relaxation parameters are used to limit the flux through cell boundaries.

Velocity calculation

The time step is determined by the maximum permissible velocity which ensures the minimum time required to distribute the applied flux distribution. The interfacial velocity v^* is calculated based on the flux transferred through a cell boundary given by:

$$v^* = \frac{F}{d \Delta x \Delta t} \tag{5}$$

where F is the flux volume being transferred between two cells, Δx is the cell size and Δt is the time step. To prevent the velocity from overshooting, a cap on the local allowable velocity is applied as given by Eq. (6) based on the Manning's formula and critical flow condition as:

$$v = \min \left\{ v^*, \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}, \sqrt{gd} \right\} \tag{6}$$

where n is Manning's roughness coefficient, R is hydraulic radius, S is water surface gradient, g is the gravitational acceleration, and d is the water depth. If v is less than v^*, the interfacial flux F is recalculated using Eq. (5).

Time-step calculation

The global time step is then calculated based on the global maximum velocity to satisfy the conventional CFL criteria. Therefore, each time state transition rule is applied, the global time step is updated by Eq. (7) as follows:

$$\Delta t = \frac{\Delta x}{\max\{\ v\}} \tag{7}$$

APPLICATION TEST CASE

An urban area at Stockbridge in Keighley, UK has been chosen (see Figure 1) as a case study. A DEM consisting of 377x269 cells with 2m resolution, obtained from LiDAR, was used for topographical representation which also forms a part of the Discrete Structure for the CA. It is assumed that there would be no flooding from the breaching of the river banks. The flooding is assumed to be solely occurred due to pluvial event. The boundary of the study area is assumed to be open, i.e., water is free to move out if the topography allows.

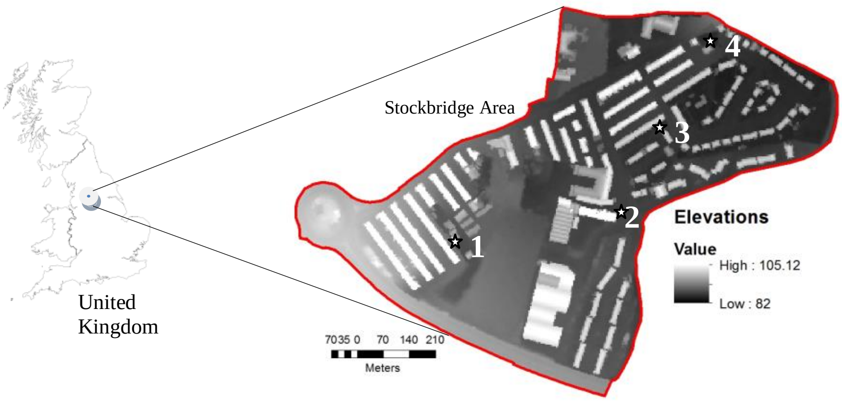

Figure 1. Study Area: Stockbridge Keighley with sample points (1~4) shown

An effective rainfall of intensity 42.3 mm/hr, which corresponds to a 100 year return period with 1-hour storm duration, is applied uniformly. The results for the maximum flood inundation depth were obtained from both the UIM and proposed CA model to compare the performance. Four sample points (1~4) are selected as shown in Figure 1 to assess the temporal variation of water depth over the space.

RESULTS AND DISCUSSION

As a basis for comparison, the physically based model UIM [3] is chosen for reference. The overall results obtained from the UIM and the CA model for maximum inundation depth show a very good agreement (Figure 2). The higher inundation depths can be observed along the lower alley areas. The temporal variation of inundation depths at selected sample points are shown in Figure 3. For points 1 and 3, the CA results are slightly higher than the

UIM results only after the peak depth occurs, however the discrepancy is not so significant. For points 2 and 4, the temporal variation of depth is in good agreement for both filling and emptying period. The overall results obtained from the CA model are in very good agreement with the UIM results. As can be seen from the figure the CA results are smoother than the UIM results. This may be due to the use of flow relaxation parameters which eventually smoothens the flow.

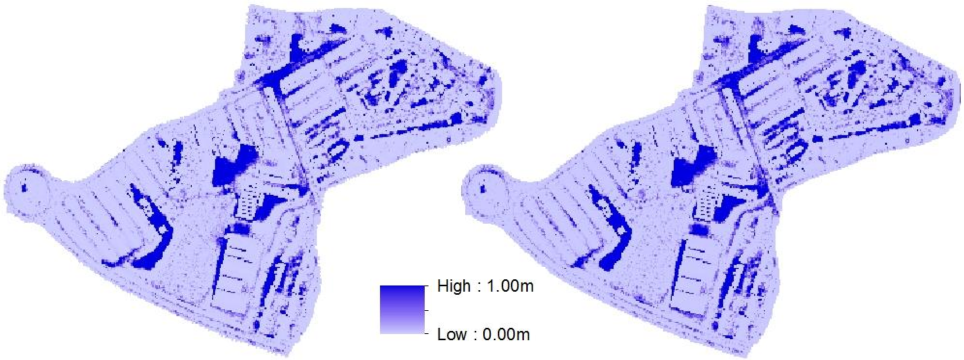

Figure 2. Maximum Inundation Depth: UIM Result (left) and CA result (right)

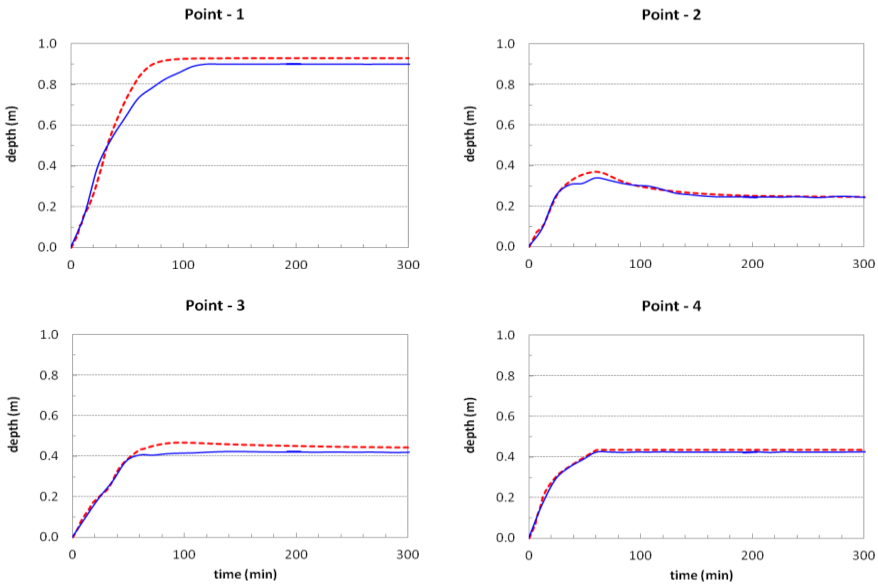

Figure 3. Temporal variation of depths from UIM (solid line) and CA (dotted line)

The computation time for the CA, when used a normal desktop computer, is much faster than it is for the UIM. For the results shown here, the CA takes about 3 minutes whereas the UIM takes 98 minutes. Our future plan is to improve the developed methodology so as to minimize the discrepancy and look into the spatio-temporal flow evolutions in more detail. The parallelisation using GPU implementation incorporating 1D underground sewer flow is also underway.

CONCLUSION

The developed 2D cellular automata model has been applied to an urban residential area in Keighley, UK. Numerical results obtained are compared with those of a physically based 2D urban inundation model UIM. Results for maximum flow depths show a good agreement. The temporal variations of depth at various selected sample points are also in agreement showing a consistent spatio-temporal evolution of the inundation process. When run on a common desktop, the CA seems to be more than 30 times faster than the UIM for the case considered in this work. It should be noted that the proposed CA algorithm is particularly suitable for parallelization and GPU computations, which would increase its applicability. The CA method can be further developed to include not only the overland flow but also associated processes, such as sewer flow, infiltration and sediment transport, etc.

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