Modelling floods in urban areas and representation of buildings with a method based on adjusted conveyance and storage characteristics

Zoran Vojinovic, Solomon Seyoum, Mwanaisha H. Salum, Roland K. Price, Ahmad K. Fikri and Yared Abebe

ABSTRACT

The present paper reviews several approaches that can be used in capturing urban features in coarse resolution two-dimensional (2D) models and it demonstrates the effectiveness of a new approach against the straightforward 2D modelling approach on a hypothetical and a real-life case study work. The case study work addresses the use of coarse grid resolutions in 2D non-inertia models. The 2D non-inertia model used solves continuity and momentum equations over the cells of the coarse model while taking the minimum elevation as a surface level. The volume stored in every cell is calculated as a volume-depth relationship. In order to replicate restriction in conveyances in *x–y* directions of fine resolution models due to building blocks, the friction values of the coarse-resolution model are adjusted to match the results of the high-resolution model. The work presented in this paper shows the possibility of applying a 2D non-inertia model more effectively in urban flood modelling applications whilst still making use of the high resolution of topographic data that can nowadays be easily acquired.

Key words | 2D models, flood modelling, spatial resolution, topography, urban areas

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ABBREVIATIONS

1D	One dimensional
2D	Two dimensional
ADI	Alternating direction
BCR	Building coverage ratio
CRF	Conveyance reduction factor
DTM	Digital terrain model
DSM	Digital surface model
GIS	Geographic information system
LiDAR	Light detection and ranging
TIN	Triangulated irregular network

INTRODUCTION

Urban flooding has become an increasingly important problem and growing issue around the world. Since it continues to be regarded as an almost inevitable danger, the development of cost-effective flood mitigation strategies has become of the utmost importance for many cities, and particularly for those cities in developing countries where the financial resources for recovery from flood-related disasters are almost nonexistent. Certainly, the use of physically-based computational modelling coupled with geographic information system (GIS) mapping is invaluable for this purpose. With instantiated models and specialist GIS flood mapping techniques it is possible to explore generation of floods and evaluate effects of different measures in response to any extreme event. Geo-referenced results from one-dimensional (1D) or 1D/two-dimensional (1D/2D) coupled models can readily be used to evaluate the potential scenario, communicate the risk of flooding and to gain insights into the nature of floods and their impacts on communities. The knowledge gained can then be transformed into a set of effective and acceptable actions to be taken by all who are affected (see, for example, Mynett & Vojinovic 2009).

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Effective communication of information and knowledge gained from flood modelling work is the key to ensuring that all those concerned have a common understanding and can jointly implement each phase of the flood risk mitigation work. For example, information from a model becomes knowledge – generating only in so far as the end user interprets that information correctly (see also Abbott & Vojinovic 2009; Abbott & Vojinovic 2010a, b). Therefore, the provision of appropriate means to enable such a communication process is a challenge that faces all those involved in flood risk mitigation.

As a consequence, there is nowadays a range of modelling approaches available for modelling floods and developing flood mitigation strategies. For much the greater part, 1D hydrodynamic models are used as a standard industry practice. More recently, however, model formulations have included a 1D representation of flow (i.e., below or above ground system) and a 2D representation of flow on urban surface (i.e., above ground system). Since the physical process of describing exchanges of flows between these two systems can be represented in different ways, the predictive capability of different modelling approaches can also vary. Furthermore, considerable attention needs to be given to the acquisition of good geometric and topographical data at adequate resolution in order to describe the primary features of the flow paths through an urban area. Given such instantiated flood models, it is then possible to begin optimising flood response actions and even introducing necessary modifications to the urban topography that are consistent with the appropriate planning criteria.

The paper reviews several approaches that can be used in capturing urban features in coarse resolution 2D models. It also attempts to demonstrate the effectiveness of a new approach that aims to capture small scale urban features which are presented in fine resolution data as we try to move from sub-grid scale to coarse resolution of 2D models. The approach used in the present work involves mathematical reformulation of the 2D numerical model to account for the change in storage and lateral fluxes for model discretization which is coarser than the available fine resolution Digital Terrain Model (DTM). This modelling approach enables more efficient model applications at coarse spatial resolutions while retaining information about the complex geometry of the urban environment. The approach is illustrated on a case study work by building several 2D models using different model discretizations (from fine to coarse) and by comparing the results against the straightforward 2D modelling approach.

URBAN FLOOD MODELLING

Traditionally, drainage systems have been modelled using a 1D approach which was limited to modelling of flows within channels and/or pipes. A step forward has been the dual drainage concept, where urban surface is treated as a network of open channels and ponds (major system) connected to the channel/pipe system (minor system), commonly referred to as 1D/1D approach. More recently, coupled 1D/2D models have emerged, in which channel/pipe network flow models are tightly coupled with the flood flow model that treats the urban surface as a two-dimensional flow domain. In these approaches, complex interactions that take place through surface/sub-surface links, are explicitly taken into account using adequate equations. Therefore, with the recent advances in numerical modelling techniques the greater majority of processes occurring within the drainage systems and urban floodplains can be represented reasonably well by the use of 1D, 1D/1D or 1D/2D modelling approaches.

The appropriate level of modelling for the assessment of particular issues depends crucially on the nature of the physical situation and on the availability of data. Where flood flows are confined to well-defined conduits, a robust 1D model can usually be instantiated and, once adequately calibrated and verified, its results may be considered reasonably safe for decision-making. However, the flows generated along urban areas are usually highly complex because the morphology of the urban surface is eminently artificial with correspondingly highly irregular geometries, and the flows may run contrary to natural flow paths. Such issues necessitate coupling of simulations using 1D and 2D modelling systems (see, for example, Hsu *et al.* 2000; Mark *et al.* 2004; Chen *et al.* 2005; Djordjevic *et al.* 2005; Mignot *et al.* 2006; Vojinovic *et al.* 2006; Verwey *et al.* 2008; Neal *et al.* 2009; Vojinovic & Tutulic 2009; Vojinovic *et al.* 2011).

Simulation using coupled 1D/2D models is a rather complex process, and as such it can take considerable computational time. These simulations are based on complex numerical solution schemes for the computation of water levels, discharges and velocities. The surface model (i.e., 2D model) simulates vertically-integrated two-dimensional unsteady flow given the relevant boundary and other ancillary conditions (e.g., resistance coefficients, etc.) and bathymetry/terrain (as provided by a digital terrain model of the catchment area); see Figure 1.

The interactions between the below-ground (or minor) and above-ground (or major) system are determined according to the type of link. For example, discharges generated by pumping stations, weirs or orifices are regarded as the lateral inflows to the 2D model. Also, if the hydraulic head of pipe flow exceeds surface water level or bank levels (for open channels) then the discharge is computed by the weir (or orifice) discharge equation and it is considered as a lateral inflow to the 2D model (that is, the source term F_s).

For 1D models, the system of 1D cross-sectional-averaged Saint-Venant equations which are used to describe the evolution of the water depth h and either the discharge Q or the mean flow velocity V consists of conservation of mass (continuity equation) and momentum (Vojinovic & Tutulic 2009; Vojinovic *et al.* 2011):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = F_s \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\beta Q^2}{A}\right) + gA\frac{\partial h}{\partial x} + g\frac{Q|Q|}{C^2AR} = 0 \tag{2}$$

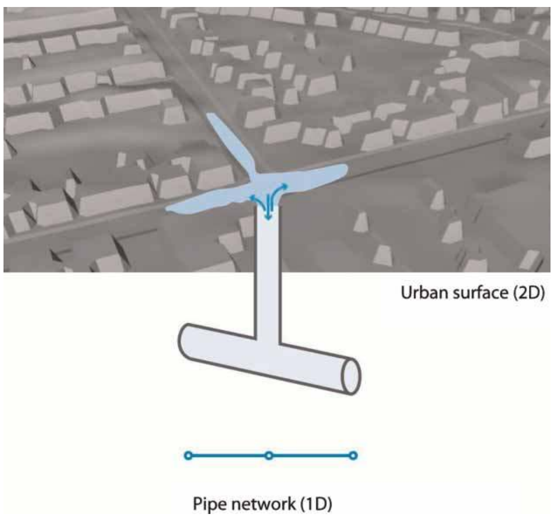

Figure 1 | Illustration of the 1D/2D model interaction.

where h is the water depth, Q is the discharge, β is the velocity distribution coefficient, x is the distance between chainages, t is time, F_s is a source term, g is the gravitational acceleration, C is the Chezy number, $A = f(h)$ is the area of the flow cross section, which is a function of water depth, $R = A/P$, is the hydraulic radius and $P = g(h)$, is the wetted perimeter.

For 2D models, the system of 2D shallow water equations consists of three equations: one continuity and two equations for the conservation of momentum in Cartesian coordinates. Mathematically, this can be expressed as (see also Vojinovic & Tutulic 2009):

$$\frac{\partial s}{\partial t} + \frac{\partial}{\partial x}Uh + \frac{\partial}{\partial y}Vh = F_s \tag{3}$$

$$\begin{aligned}\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + g\frac{\partial s}{\partial x} + \frac{g}{C^2d}U\sqrt{U^2+V^2}\\ + \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial U}{\partial y}\right) = F_sU_s\end{aligned} \tag{4}$$

$$\begin{aligned}\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + g\frac{\partial s}{\partial y} + \frac{g}{C^2d}V\sqrt{U^2+V^2}\\ + \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial V}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial V}{\partial y}\right) = F_sV_s\end{aligned} \tag{5}$$

where s is the water surface elevation, U and V are depth-averaged velocities, K_{xx} and K_{yy} are eddy viscosities and U_s and V_s are the velocities at the source.

In general terms, 2D flow simulation can be done on a structured or unstructured mesh – regular or irregular grid. The former approach may appear more convenient as it can directly use Light Detection And Ranging (LiDAR) DTM data, thus has a simpler (matrix) data structure and is consequently easier to code. The latter, however, captures surface features much more efficiently, using triangulated irregular network (TIN), which adapts computational mesh to match boundaries of buildings, curbs, etc.

The following discussion concerns setting up of 2D models with regular grids and representation of buildings.

REPRESENTATION OF BUILDINGS IN 2D MODELS

Floodwaters flowing through urban areas follow different kinds of paths as the water moves through and around buildings, fences and other obstructions. Such obstructions tend to dissipate energy by forcing the water to change its direction and velocity, and by forming eddies behind them. Therefore, the rising and lowering of water levels together with the estimation of flow velocities, flow directions, flood durations and inundation extents are important aspects and need accurate representations. For such representations and consequent interpretations, sufficiently detailed and accurate representation of the topography plays a key role. DTMs or Digital Surface Models (DSMs) created from ground surveys or LiDAR data are often utilised for this purpose. Typically, such data can be processed to represent either the land surface alone (Figure 2(a)), land surface with the road network (Figure 2(b)) or land surface together with the road network and buildings (Figure 2(c)). Furthermore, in case of buildings with underground car parks, such objects can be represented as storage, Figure 3 (see also Abdullah *et al.* 2012a, b).

It is fair to say that 2D models with higher grid resolutions will enable better description of physical processes over the urban floodplain than the models with coarser grid resolutions. However, computing resources still restrict the applications when very detailed information is demanded over a very large area. Increasing the grid size

Figure 3 | Example of underground car park buildings represented as a storage within a DTM (see Abdullah *et al.* 2012a, b).

can effectively improve efficiency, but also can necessitate reductions in details. For instance, elevations of buildings represented in fine-grid models would be smeared or completely removed when the grid is coarsened. For this reason, the straightforward 2D modelling technique may not reflect properly the local flow phenomena in coarse-grid applications, in which case an alternative modelling approach needs to be sought. Illustration of impacts of a gradual increase of 2D model grid size on buildings and roads is given in Figure 4.

Since the buildings can have a considerable influence on the characteristics of flood flow behaviour, several approaches have been developed to date to represent their

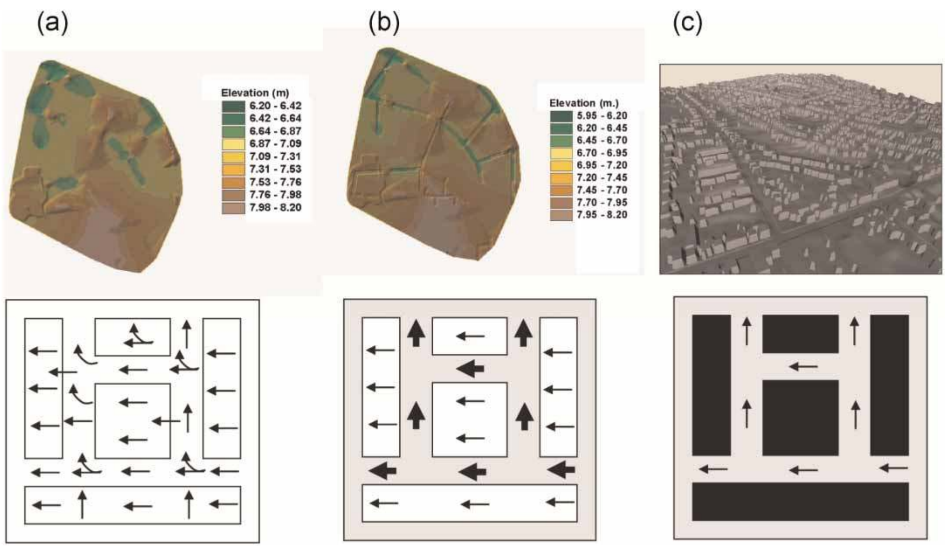

Figure 2 | Schematisation of flow paths in urban areas: (a) DTM only – buildings and roads are represented as hollow objects; (b) DTM with road network (this can be achieved by lowering the road network elevation relative to the land surface); (c) DTM with buildings and roads represented as solid objects (this can be achieved by lowering the road network elevation relative to the land surface and raising the building elevations above the land surface) (Vojinovic & Tutulic 2009).

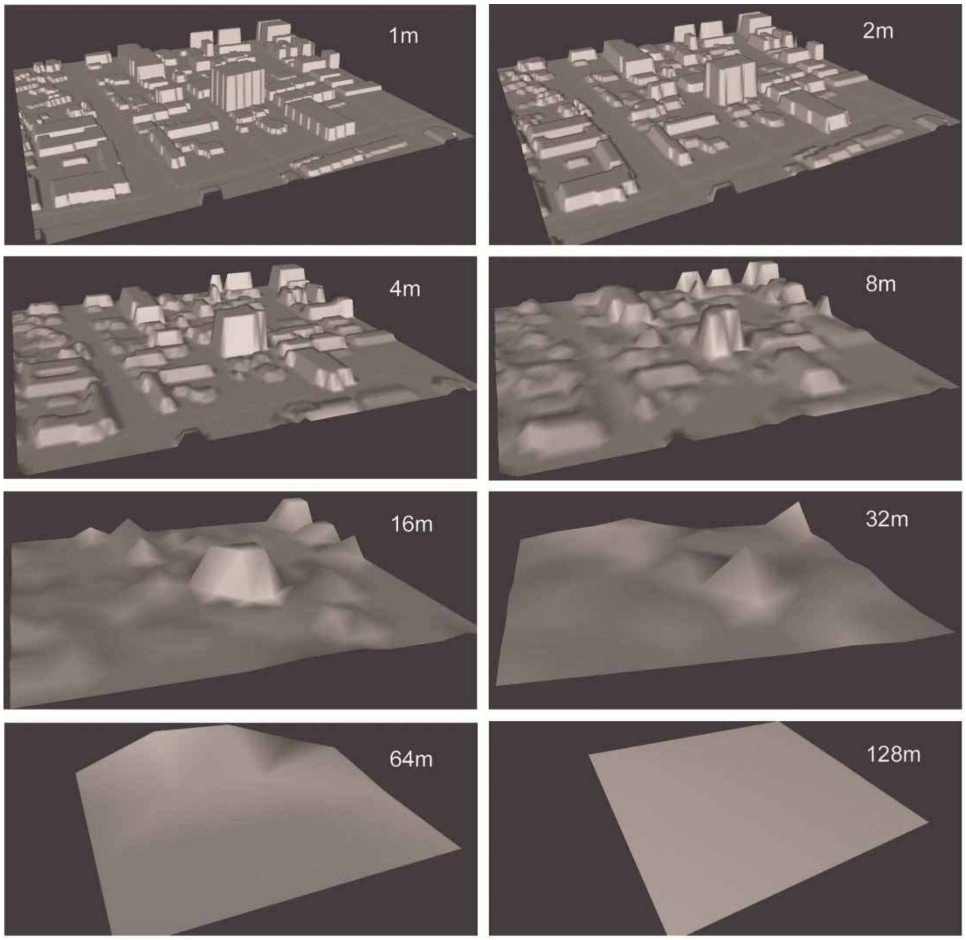

Figure 4 | Effects of a grid resolution on capturing buildings and road features (catchment area size is 7 ha). The grid size is displayed in the top-right corner. The road features have completely disappeared at 8 m grid size and most of the buildings have disappeared at a 16 m grid size. Approximately 95% of the all floodplain features have disappeared at a 32 m grid size. All the floodplain features have disappeared at a 64 m grid size (Vojinovic & Abbott 2012).

influence. Some of these approaches are described in Vojinovic & Abbott (2012) and include the following methods.

Increased model roughness for building footprints

This method might be more suitable for coarse meshes where groups of cells are used to represent the bulk effect on flow of building groups (as opposed to individual buildings) (Figure 5). It allows for storage effects and it also allows for variation of the roughness parameter to apply calibration to field data (Syme 2008). In terms of practical applications, this approach can be found troublesome as it is difficult to come up with appropriate roughness values, and since the friction factor holds a strong relationship to velocity, calibration to a single event can be unreliable (Alcrudo 2002; Yu & Lane 2006; Fewtrell *et al.* 2008).

Blocking out model elements for building footprints by raising the cell elevations to a height that is above the flood level or lowering the cell elevations for those buildings that may act as storage areas

This approach can produce a flow pattern that is visually consistent with the conditions on the ground (Figure 6). In this approach, it is important to elevate the bed of the building footprint cells to a certain height to ensure that the building is correctly represented (i.e., that the water level will not overtop the building) (see also Brown *et al.* 2007). It should be noted that using abrupt bottom elevations

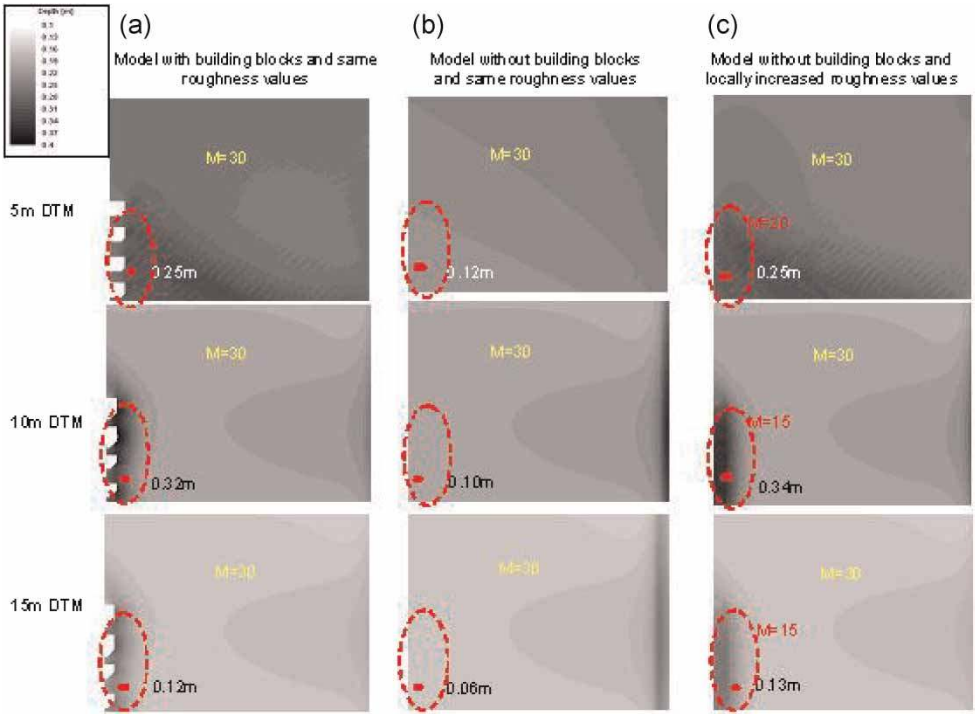

Figure 5 | 2D model results (depths) for different DTM resolutions representing buildings as solid blocks (a), not representing buildings at all (b) and buildings represented with locally increased roughness values. The roughness values are the same throughout the 2D model domain for cases (a) and (b), i.e., Manning's value of 30 was used, whereas in case (c) the roughness values of cells within the building footprints have been altered (i.e., Manning's value of 20 was used). The flow was introduced in the direction from east to west (see also Vojinovic & Abbott 2012).

changes violates the shallow water equation assumption that the bed slope is sufficiently small to ensure that the sine and tangent of the slope are close in value to an angle itself. However, as the flow is propagating around the buildings, this assumption may not necessarily be violated (see Alcrudo 2002). It should also be noted that the

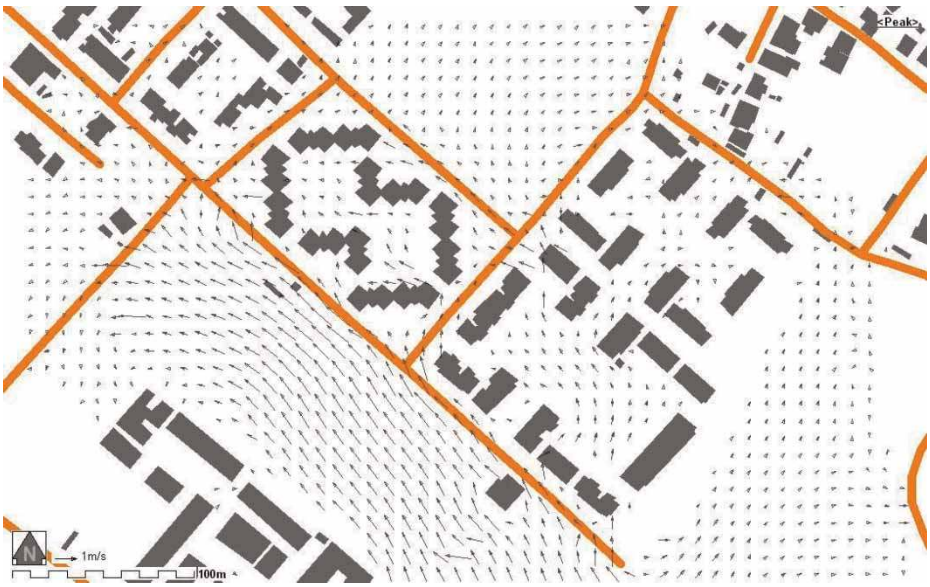

Figure 6 | Example of 2D modelling of flows around buildings (Vojinovic & Abbott 2012).

representation of buildings through increased bed elevations can destabilise numerical solutions unless limiting conditions are introduced.

Using an energy-loss coefficient over the building footprints

As an alternative to the first approach, which is based on an increased Manning's n value (i.e., *increased model roughness for building footprints*), it is also possible to specify form- (and consequent energy-) loss coefficients to represent the fine-scale energy dissipation within and around buildings. This can be more correct as the energy-loss occurs mainly due to the water contracting and expanding as it flows through and around buildings. Although a 2D scheme accounts for some of these form losses (e.g., the expansion of water downstream of the building), the fine scale losses that are not well represented, need to be included: hence the need for additional energy dissipation terms. Similarly to the first approach described above (i.e., *increased model roughness for building footprints*), this approach can also be troublesome as it is difficult to know what would be the appropriate form-loss values in advance.

Modelling buildings as 'porous' elements

This method requires modification of the shallow water equations and it may not be found feasible for applications where commercial software is used in the modelling work. For further examples and discussions, see Alcrudo (2002), Guinot & Soares-Frazão (2006), Sanders *et al.* (2008), and Soares-Frazão *et al.* (2008).

Representing buildings with adjusted conveyance characteristics

This method requires adjustment of conveyances in *x*–*y* directions to account for effects of building blocks and similar to the previous method it may not be found feasible for applications where commercial software is used in the modelling work. For further examples and discussions of this approach, see Evans *et al.* (2009), Evans (2010), Salum (2010) and Chen *et al.* (2012).

In addition to the modelling of buildings, it should be noted that other urban features such as curbs, roads, stairs, fences, cars, morphological objects, etc. should be carefully considered as they could also have an important role in diverting the flow of flood water through urban areas.

Since the straightforward 2D modelling technique may not reflect properly, the local flow phenomena in coarse-grid applications further adjustments of the 2D modelling approach are necessary. The following discussion focuses on the representation of the key features within coarse grid resolutions.

REPRESENTATION OF KEY FEATURES WITHIN COARSE GRID RESOLUTIONS

Representation of key features within coarse models can be undertaken in several ways. As described in Vojinovic & Abbott (2012), some of the common approaches are as follows.

A method based on sub-grid scale porosity treatment and adjustment of storage characteristics

Example of this approach is an approach adopted by Yu & Lane (2006) which represents fine-scale characteristics within a coarse grid using sub-grid parameterization. Yu & Lane (2006) introduced a 'porosity' function within the coarse model; this was used as a means of maintaining the slope integrity of a surface within the coarse representation. McMillan & Brasington (2007) adopted a similar approach in their work, whereby fine-scale topology is also represented within coarse grids in terms of its 'porosity'. The fine-scale topology provides information ascertaining to where water can enter the coarse grid and the direction it can leave. This relationship is dependent on the depth of water within the cell and is defined in this instance as its 'porosity' referenced within a lookup table. A volume–depth relationship is created based on the percentage of the cell volume above the ground surface and hence available for water storage. Such approach enables modelling urban features at coarse resolutions with little increase in computational costs (see also Soares-Frazão *et al.* 2008).

A method based on adjusted conveyance and storage characteristics

A method based on adjusted conveyance and storage characteristics represents a new methodology that can be used to reproduce similar flow characteristics along the floodplain between fine and coarse 2D model resolutions. This approach necessitates computation of a volume-depth relationship for transition between fine and coarse cells (see Figure 7). The 2D model solves continuity and momentum equations over the cells of the coarse model while taking the minimum elevation as a surface level. In this way, for each depth increment, the volume stored in every cell is calculated as a volume-depth relationship. The same is then applied for the area-depth relationship, and for every increase in depth the area filled with water is calculated.

In order to replicate restriction in conveyances in x–y directions of fine resolution models due to building blocks, the friction values of the coarse-resolution model can be adjusted to match the results of the high-resolution model. This approach is demonstrated in the case study work of the present paper.

A multilayered approach

In Chen *et al.* (2012), the area occupied by buildings within coarse grids is represented numerically with the use of a Building Coverage Ratio (BCR) and the restriction of surface flow propagation from one coarse cell to another was governed by the Conveyance Reduction Factor (CRF). This approach, however, allows for different BCR and CRF values to be assigned to each coarse grid cell. A multilayered approach is then achieved by representing effects of buildings numerically within a multiple layer grid format (see Evans *et al.* 2009; Evans 2010). In Evans 2010, the transformation from a fine-grid DTM into a coarse-grid multi-layered representation was initially done by generating a Boolean building grid representation of the terrain for reference, and then, using this information, coupled with a discretizing window, the DTM is then broken up into layers using a Cellular Automata methodology.

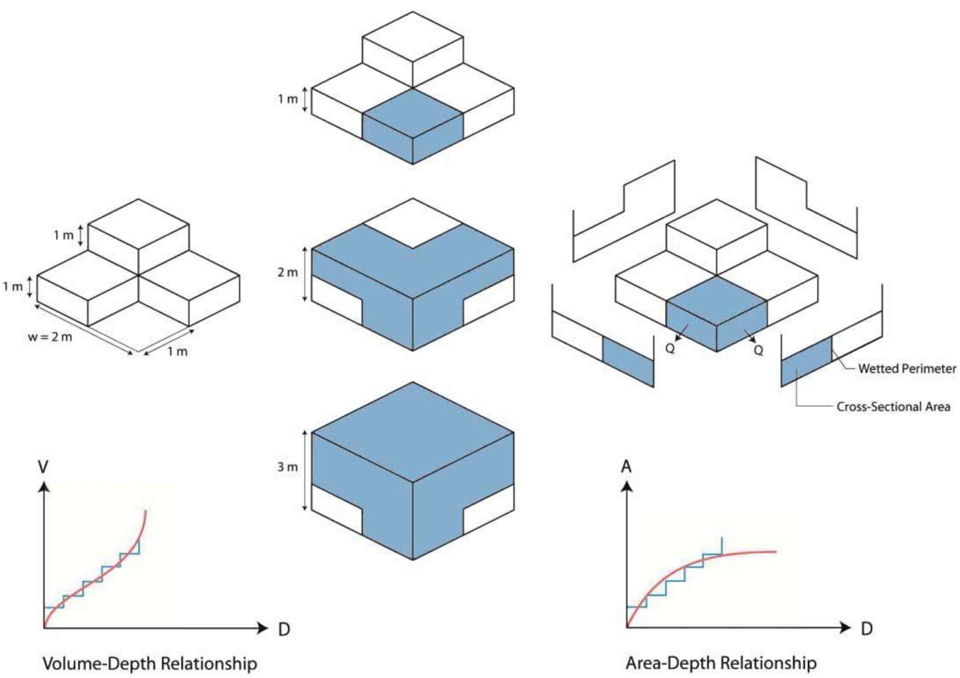

Figure 7 | Illustration of volume-depth and area-depth relationships within a cell.

An approach based on multi-cell finite difference solver as implemented in some commercial packages

The multi-cell finite difference solver for overland flow has been implemented in MIKE FLOOD and MIKE 21 systems and it offers a number of advantages in comparison to the regular finite difference solver. This technique offers a reduction in model runtime by a factor of 5–10 when compared with a standard 2D finite difference solution to the Saint-Venant equations. The Multi-cell Difference Solver uses a coarse scale topographical data to carry out time-varying water surface and 2D flow velocity calculations, while the fine scale topographical data are utilised to produce depth distribution within a course grid cell (Hartnack *et al.* 2009).

The present work concerns the second approach (i.e., which is a new method based on adjusted conveyance and storage characteristics) and it demonstrates its effectiveness on two case studies: hypothetical case and real-life case of an urban catchment in Kuala Lumpur (Malaysia). The following text describes the case study work and the findings.

CASE STUDY WORK

Description of models

For the purpose of addressing the issue of representing urban features in coarse grid resolutions, a 2D non-inertia model developed and described in Seyoum *et al.* (2012) was used. Equation (6) shows an implicit finite difference form of the reduced equations of that model.

For each cell in the coarse grid model, the relationship between the water surface elevation and the volume of water that can be stored within the corresponding cells of the fine grid model was calculated. Similarly, the relationship between the water surface elevation and the conveyance area was also calculated for the same cells. These relationships are produced from the actual cell values of the fine grid model and not by their averaging. Thus, depending on cell elevations the resulting relationships could have different form: linear (e.g., the flat plain case study shown in Figure 12) or non-linear (e.g., a case concerning real-life catchment area); see also illustration given in Figure 7.

The resulting finite difference equations are, however, still non-linear, so the Newton-Raphson iterative method can be used to solve them at each time step. This results in a set of linear equations in the increments to the water levels in each cell. The resulting matrix can be inverted and the solution for the increments to the water levels can be found. Iteration can be carried out if the magnitude of the maximum increment is too large. The iterations are concluded if the magnitude of the maximum increment is acceptable. The calculations then proceed to the next time step.

A problem with this solution is that the number of arithmetical operations involved in inverting the matrix, and therefore the computational time, is at least proportional to N^3, where N is the smaller number of cells in the x- or y-directions. An alternative numerical solution has been derived using the alternating direction (ADI) method whereby the velocities in the x-direction are calculated at the half time step, and the velocities in the y-direction at the full time step; see Figure 8. Therefore, the ADI method has been implemented in the present 2D model.

$$\frac{1}{\Delta t}\left(\frac{Q_{i+1,j}^{n+(1/2)}}{A_{i+1,j}^{n+(1/2)}}-\frac{Q_{i+1,j}^{n-(1/2)}}{A_{i+1,j}^{n-(1/2)}}\right)+g\theta\frac{h_{i+1,j}^{n+(1/2)}-h_{i,j}^{n+(1/2)}}{\Delta x}$$
$$+g(1-\theta)\frac{h_{i+1,j}^{n-(1/2)}-h_{i,j}^{n-(1/2)}}{\Delta x}$$
$$+\theta\frac{1}{K_{i+1,j}^{n+(1/2)^2}}\frac{Q_{i+1,j}^{n+(1/2)}}{A_{i+1,j}^{n+(1/2)}}\sqrt{\left(\frac{Q_{i+1,j}^{n+(1/2)}}{A_{i+1,j}^{n+(1/2)}}\right)^2+\bar{v}_{i+1,j}^{n2}}$$
$$+(1-\theta)\frac{1}{K_{i+1,j}^{n-(1/2)^2}}\frac{Q_{i+1,j}^{n-(1/2)}}{A_{i+1,j}^{n-(1/2)}}\sqrt{\left(\frac{Q_{i+1,j}^{n-(1/2)}}{A_{i+1,j}^{n-(1/2)}}\right)^2+\bar{v}_{i+1,j}^{n2}}=0$$

$$\frac{1}{\Delta t}\left(\frac{R_{i,j+1}^{n+1}}{A_{i,j+1}^{n+1}}-\frac{R_{i,j+1}^{n}}{A_{i,j+1}^{n}}\right)+g\theta\frac{h_{i,j+1}^{n+1}-h_{i,j}^{n+1}}{\Delta x}+g(1-\theta)\frac{h_{i,j+1}^{n}-h_{i,j}^{n}}{\Delta x}$$
$$+\theta\frac{1}{K_{i,j+1}^{n+1\,2}}\frac{R_{i,j+1}^{n+1}}{A_{i,j+1}^{n+1}}\sqrt{\left(\frac{R_{i,j+1}^{n+1}}{A_{i,j+1}^{n+1}}\right)^2+\bar{u}_{i+1,j}^{n+(1/2)2}}$$
$$+(1-\theta)\frac{1}{K_{i,j+1}^{n\,2}}\frac{R_{i,j+1}^{n}}{A_{i,j+1}^{n}}\sqrt{\left(\frac{R_{i,j+1}^{n}}{A_{i,j+1}^{n}}\right)^2+\bar{u}_{i+1,j}^{n+(1/2)2}}=0$$

$$\frac{1}{\Delta t}\left(V_{i,j}^{n+(1/2)}-V_{i,j}^{n-(1/2)}\right)+\theta(Q_{i+1,j}^{n+(1/2)}-Q_{i,j}^{n+(1/2)})$$
$$+(1-\theta)(Q_{i+1,j}^{n-(1/2)}-Q_{i,j}^{n-(1/2)})+(R_{i,j+1}^{n}-R_{i,j}^{n})=q$$

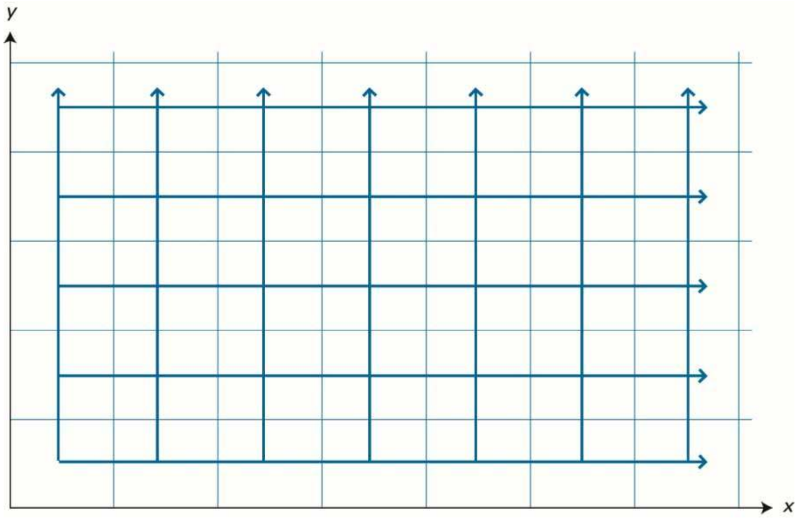

Figure 8 | Schematics of the ADI approach of the 2D model used in the present work.

$$\frac{1}{\Delta t}\left(V_{i,j}^{n+1} - V_{i,j}^{n}\right) + (Q_{i+1,j}^{n+(1/2)} - Q_{i,j}^{n+(1/2)}) + \theta(R_{i,j+1}^{n+1} - R_{i,j}^{n+1}) + (1-\theta)(R_{i,j+1}^{n} - R_{i,j}^{n}) = q \quad (6)$$

Here $Q_{i+1,j}^{n+(1/2)}$ is the discharge across the cell boundary in the x-direction; $R_{i,j+1}^{n}$ is the discharge across the cell boundary in the y-direction; K is roughness factor which can be expressed using Chezy or Manning equations, and V is volume stored in the grid.

The numerical solution then resolves into solving for the water levels in the cells for a series of 1D channels, first in the x-direction and then in the y-direction. The water levels are determined at the cell centres and the discharges (or velocities) are determined at the cell boundaries. The solution procedure for a single channel is outlined above. The non-linear difference equations were solved using Newton-Raphson, but solving for the whole domain before testing the maximum increment in water level. This enables to decide whether or not to repeat the iteration in order to refine the estimates of the solution for the water levels. The model can adjust its time step, halving it if the increments in water level fail to converge within a required number of iterations, or doubling the time step if the convergence has been satisfied for a further number of time steps; see also Price & Vojinovic (2011) and Seyoum et al. (2012).

In terms of the integration of the 1D pipe network model with the 2D overland flow model, the method for linking the two models used in the present work assumes that flow emerging from a manhole spills out radially into an above-ground 2D cell via a circular orifice, with the flow determined by the difference in water level between the manhole and the cell. The discharge emerging from the manhole during the time step is input as a source to the 2D model (see Figure 9). The 2D model then computes the resulting overland flow for a number of time steps for duration equal to the 1D time step (normally the

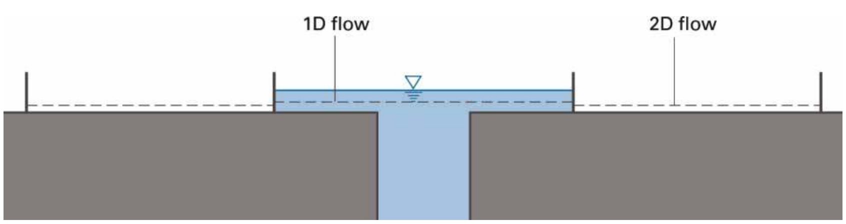

Figure 9 | Illustration of interaction of 1D and 2D flow at a manhole.

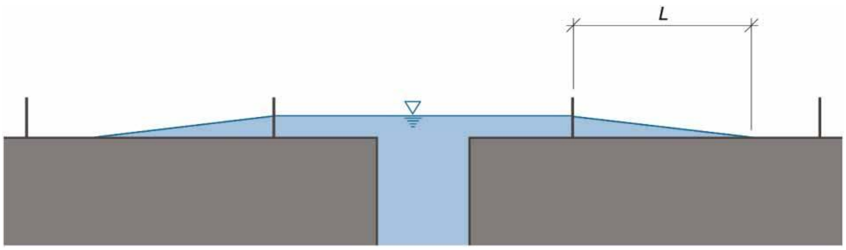

Figure 10 | Illustration of 2D flow of water from a manhole on a flat surface.

2D model time step will be smaller than the 1D time step). The calculation then returns to the 1D model using the latest water levels at the manhole and in the cell containing the manhole. See Figure 10 for an illustration of this integrated approach. The 1D model which was used as a source to the 2D model in the hypothetical case study work is SWMM model (see Rossman *et al.* 2005).

The 2D model is then able to cater for the flow emerging from a manhole and flowing over a dry surface. The condition at the front is also important. Here it is assumed that the front propagates across a cell with a velocity at any instant equal to the velocity u of the inflow to the cell (see Figure 11). The cell is assumed to be wet (and the front can move to the next dry cell) when

$$L = \sum_t u\Delta t < \Delta x \tag{7}$$

where L is the cumulative distance (m) that the front travels within the cell since first arriving.

Note that on a sloping surface the front propagates at the speed associated with the (approximate) normal depth upstream which is used at the beginning of the computation. Such a normal depth cannot exist on a flat surface, but the propagation is determined by the local velocity, which is a function of the time history of the forcing flow from the manhole(s), and possibly the rainfall runoff.

In the following case study work, the effectiveness of the two modelling approaches was compared:

1. the straightforward 2D modelling approach without any adjustments, and
2. the new method based on adjusted conveyance and storage characteristics.

Discussion of the case study work

Initially, a hypothetical case study work concerning flat and sloping surface was carried out. The purpose of this work was to verify the usefulness of the new approach on a relatively simple case that can be easily followed. Figures 12 and 13 show results for 2D calculations for flow from a manhole (i.e., 1D model) on flat and sloping beds with a 1×1 m and a coarse 5×5 m grid, respectively. For the flat bed, the source (i.e., surcharge from a manhole) is placed at the centre, whereas for the sloping bed the source is placed close to the edge of the left side of the 2D model domain. The results obtained demonstrate the capability of the new

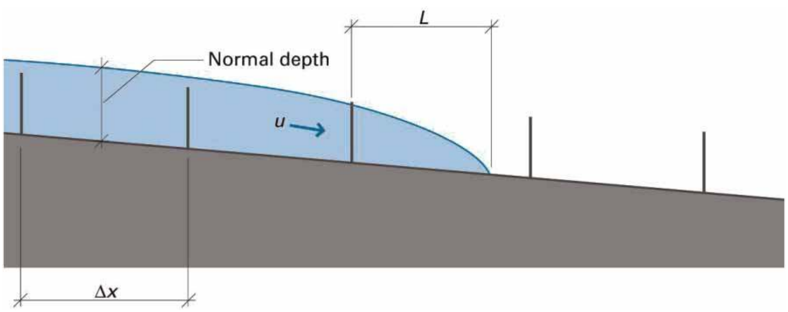

Figure 11 | Illustration of propagation of a front over a dry bed on a sloping surface with the wide rectangular cross-section.

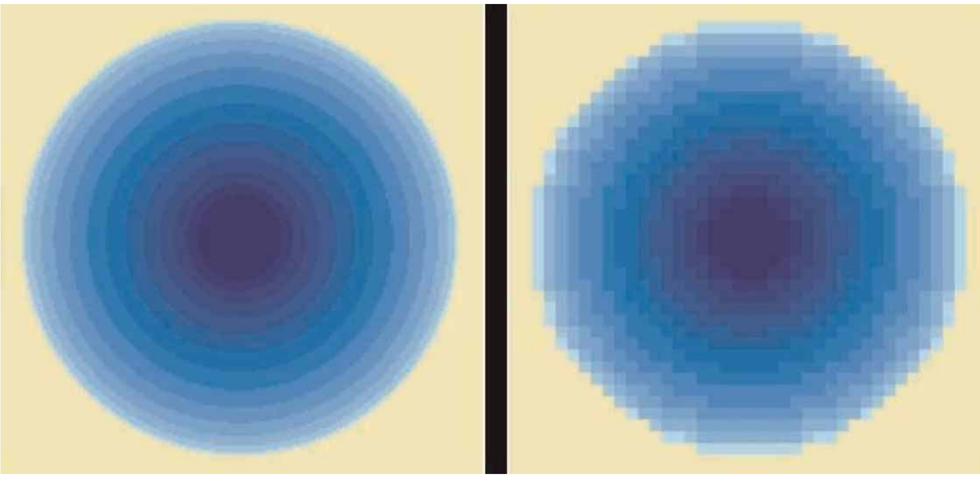

Figure 12 | Overflowing manhole on a flat plain: fine resolution (1 × 1 m) and coarse resolution (5 × 5 m).

method based on adjusted conveyance and storage characteristics to represent flood depths and flood extent in a similar manner. In this initial case, no building blocks were modelled.

The second case study work concerns a real-life catchment area which is situated in the Klang River basin in Kuala Lumpur, Malaysia. This area is located on the west coast of Peninsular Malaysia in Federal Territory of Kuala Lumpur. The Klang River basin is the most densely populated area of the country with an estimated population of over 3.6 million and growing at almost 5% a year. Even though the major flood mitigation works within the Kuala Lumpur region have been implemented, flooding in the city is still frequent and severe. Consequently, several studies were conducted to address these issues and some of them included the use of numerical models.

The model of the study area contains the river network and urban floodplains for which the 1D/2D commercial software packages MIKE11/MIKE21 (i.e., MIKEFLOOD) were utilised. In one of the earlier studies, the time series measurements were collected from the Klang River and used as such in the calibration of MIKE11 model (DHI 2004). Subsequent to that, MIKE21 model was built from the high quality LiDAR survey data (where the building blocks were retained and all morphological objects were removed) and that model was cross-validated according

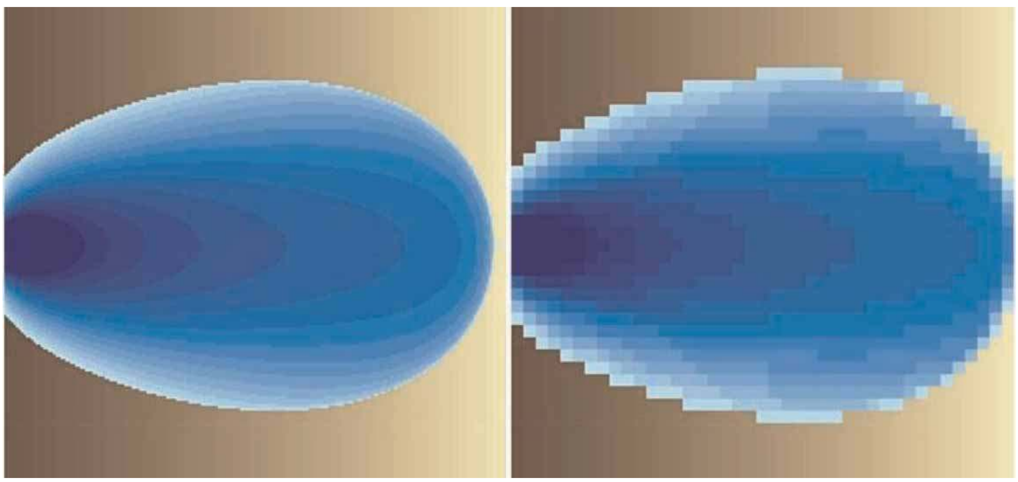

Figure 13 | Overflowing manhole on a sloping plane: fine resolution (1 × 1 m) and coarse resolution (5 × 5 m).

to the water depth records taken during rainfall events at several locations across the study area (Abdullah *et al.* 2012a, b).

The 2D non-inertia model described above was set to represent the study area and it was calibrated against the existing MIKE21 model. This was done to compensate for the absence of the actual time series measurements. The model calibration process was carried out by adjusting roughness coefficients to fit with the flood depths obtained from the MIKE21 model results (i.e., MIKE 21 model results were used as the benchmark for 2D non-inertia model). In the 2D non-inertia model, urban topography is represented by the ground elevations set at the centres and boundaries of cells on a rectangular Cartesian grid. The schematization of the topography coupled with the way the governing equations are solved allows for a good representation of small-scale topographical elements across urban floodplains including well-defined flow paths such as road networks and channels. The model was set to simulate effects from a dyke breach along Klang River and corresponding propagation of flow throughout an urban area. The breach discharge was set to gradually increase from 0 to 8 $m^3 s^{-1}$ over a period of one hour (see Figure 14).

In order to test the effects of spatial scale, the original DTM was aggregated to six progressively coarser resolution DTMs (i.e., 2×2 m, 4×4 m, 6×6 m, 8×8 m, 10×10 m and 12×12 m) using standard interpolation techniques.

The standard approach to modelling floods across urban floodplains is to calibrate roughness coefficients according to observed parameters of the flood (which is in this case the flood depths using the calibrated MIKE21 model as the benchmark). However, it should be noted that the values of the friction parameters are scale-dependent and within high-resolution models these values account for a variety of small scale features and unrepresented processes and compensate for a combination of drag forces aligned in the flow direction and shear stresses acting on the sides of the flow, whereas in coarse-resolution models these values also account for a lack of physical process representation in the controlling equations as well as resistance to the flood flow.

In the present case study work, a uniform Chezy value of 30 was used in the 2×2 m benchmark model simulation. After that, five simulations concerning different grid resolutions (i.e., 4×4 m, 6×6 m, 8×8 m, 10×10 m and 12×12 m) were carried out using different 2D modelling techniques. The 2D non-inertia model was adjusted to account for conveyance and storage characteristics according to the procedure described above. In this process, a range of Chezy values (from 22 to 30) was used and storage characteristics were calculated according to the volume-depth

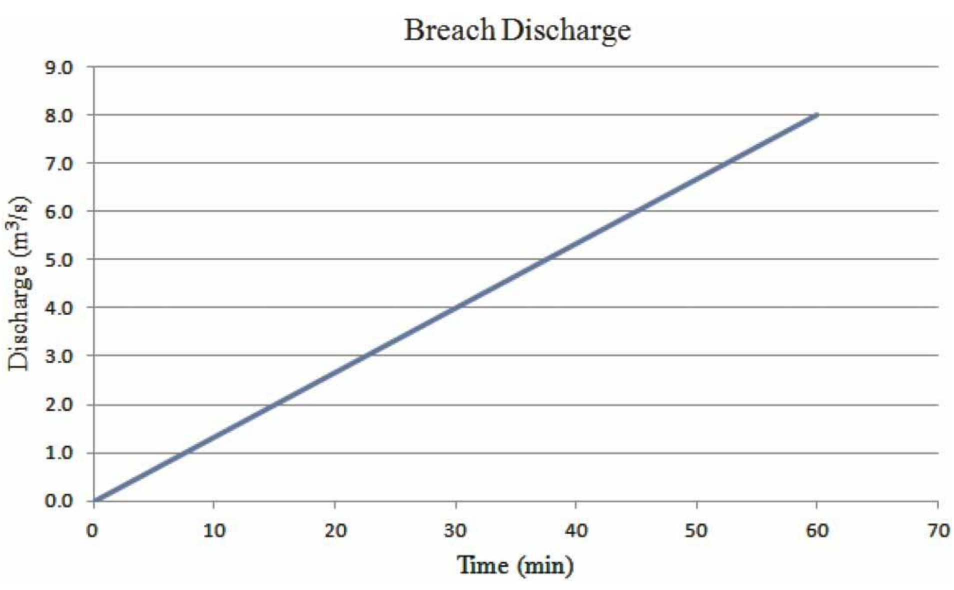

Figure 14 | Breach discharge hydrograph.

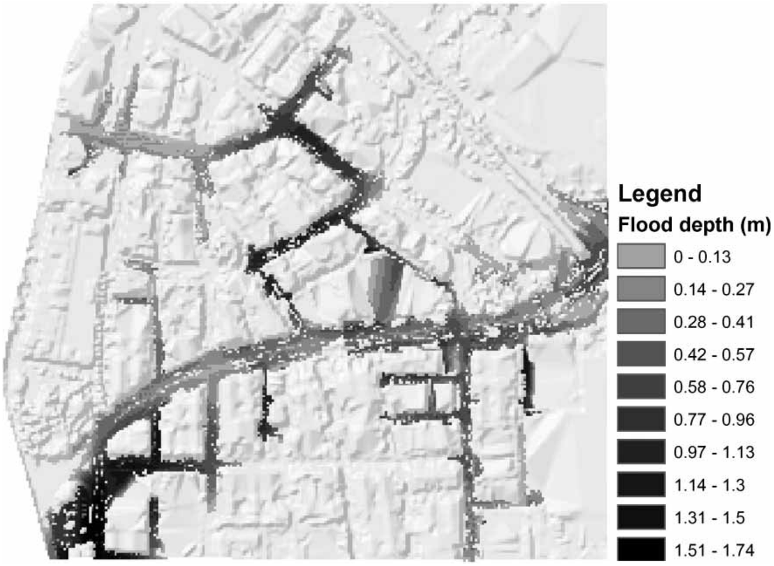

Figure 15 | Maximum flood depth for the fine grid (2 × 2 m) model using the straightforward 2D modelling approach.

and area-depth relationships. Finally, the comparisons were carried out for:

1. the results obtained from the straightforward 2D modelling approach without any adjustments, and
2. the results obtained from a new method based on adjusted conveyance and storage characteristics.

The model results concerning the straightforward 2D modelling approach are shown in Figures 15 and 16, whereas the model results concerning a new method based on adjusted conveyance and storage characteristics are shown in Figures 17–21.

The summary of the model results concerning Kuala Lumpur case study are given in Table 1. They are expressed

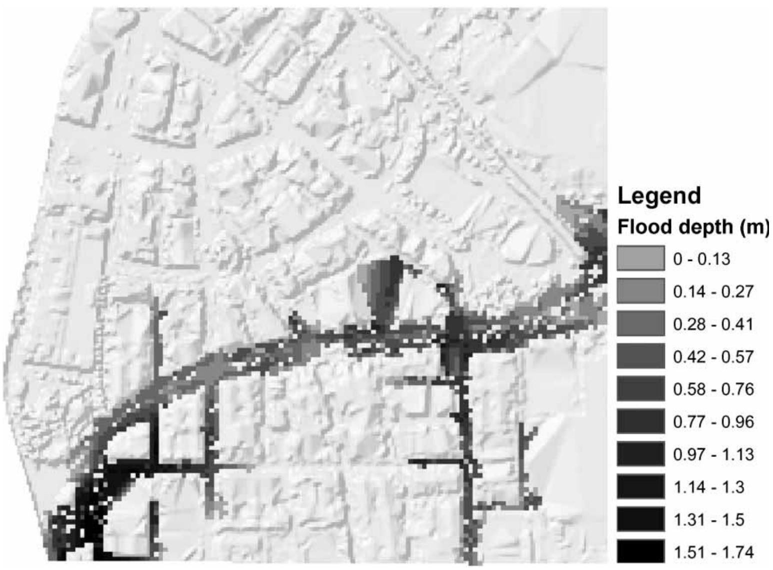

Figure 16 | Maximum flood depth for the coarse grid (4 × 4 m) model using the straightforward 2D modelling approach.

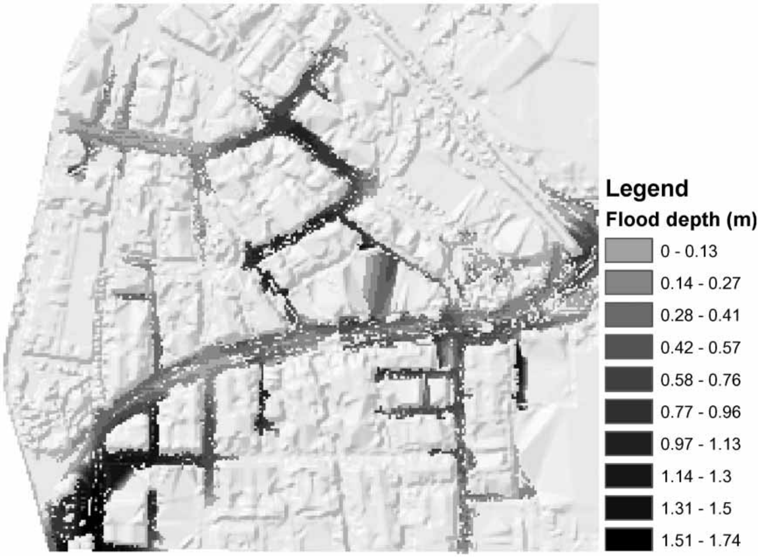

Figure 17 | Maximum flood depth for the coarse grid (4×4 m) model using the method based on adjusted conveyance and storage characteristics.

in terms of the number of flooded cells in 2×2 m DTM, flood volume, average depth and computational time.

Several important points emerge from the above presented results. Perhaps, as expected, the most important point is that the straightforward 2D modelling technique is not capable of reducing dependence of accuracy upon grid resolution. The next important point is that the new method based on adjusted conveyance and storage characteristics described above is effective in reducing simulation dependence upon grid resolution and producing the results which are similar to the results of higher resolution model (i.e., 2×2 m model). Comparison of the number of flooded cells when projected onto 2×2 m DTM (i.e., inundation extent) and inundation depths obtained using different model resolutions shows that the straightforward 2D modelling approach is quite sensitive to spatial

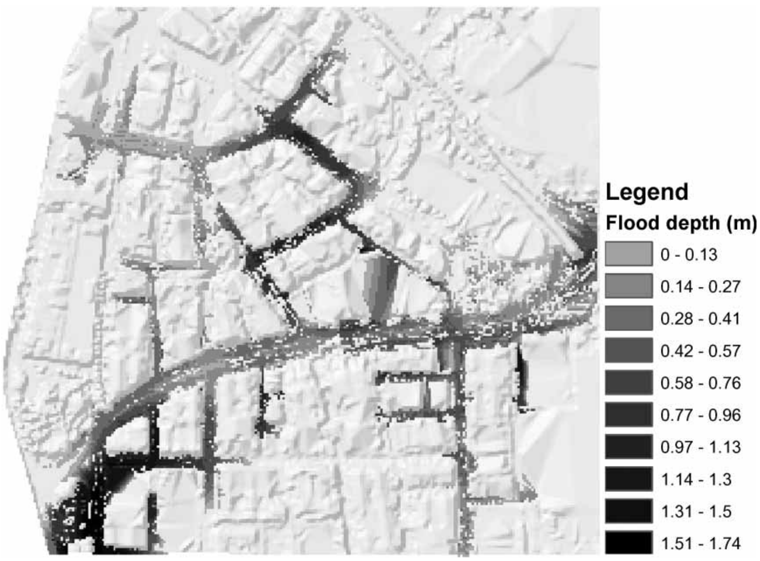

Figure 18 | Maximum flood depth for the coarse grid (6×6 m) model using the method based on adjusted conveyance and storage characteristics.

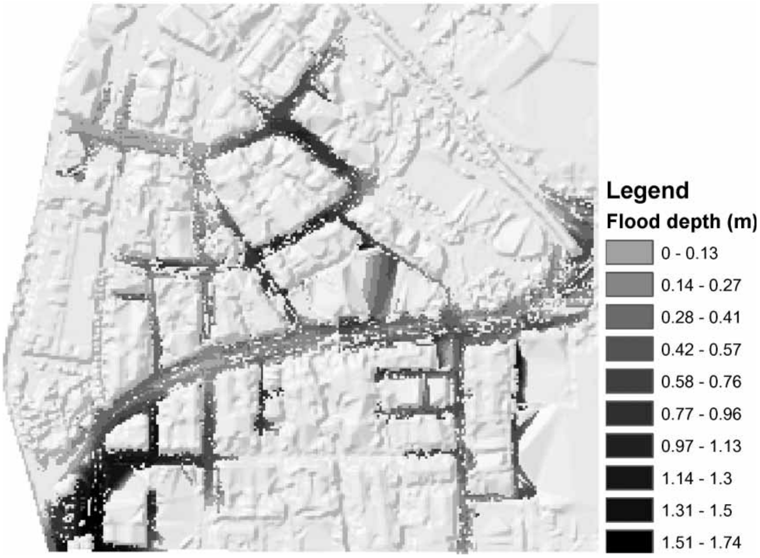

Figure 19 | Maximum flood depth for the coarse grid (8×8 m) model using the method based on adjusted conveyance and storage characteristics.

resolution with respect to both the inundation extent and inundation depth. This can be explained by the smoothing effects of mesh coarsening and smeared representation of buildings (as well as other urban features) and surface routing processes as the mesh is coarsened. For example, the straightforward 2D modelling approach with a 4×4 m resolution produced 3098 flooded cells (34% of the total number of flooded cells produced by 2×2 m model), whereas the new 2D modelling approach based on adjusted conveyance and storage characteristics in the same 4×4 m resolution produced 9067 (which is 98% of the total number of flooded cells produced by 2×2 m model). For the 6×6 m grid resolution case, the total number of flooded cells produced by the new 2D modelling approach based on adjusted conveyance and storage characteristics is 9031 (which is also 98% of the total number of flooded cells produced by 2×2 m model) and so on. Also, in terms of inundation depths, the difference observed ranged from 0.375 m to 0.428 m which is in

Figure 20 | Maximum flood depth for the coarse grid (10×10 m) model using the method based on adjusted conveyance and storage characteristics.

Figure 21 | Maximum flood depth for the coarse grid (12 × 12 m) model using the method based on adjusted conveyance and storage characteristics.

the range of 97% (or 3% underestimation) to 111% (or 11% overestimation). For the straightforward 2D modelling approach, the difference for 4 × 4 m resolution was 145% (or 45% overestimation). Therefore, for a case study area used in the present work, not only that the total inundated area is substantially different with coarser resolutions using the straightforward 2D modelling approach, but also the inundated depths were also significantly different. It appears that there is a strong sensitivity of the 2D straightforward 2D modelling approach to mesh resolution in terms of inundated area.

In terms of computational time, it can be observed that the model with higher resolution needed much longer computational time than the coarser models, roughly proportional to the number of grid cells. It is also worth noting that the new method based on adjusted conveyance

Table 1 | Comparison of model results. Note that for comparison purposes, the number of cells was calculated by superimposing the coarse model results onto the 2 × 2 m DTM and by summing up the corresponding flooded cells

Grid resolution (m*m)	Model type	No of flooded cells in the 2 × 2 m DTM	Average depth (m)	Computation time (min)
2 × 2	Straightforward 2D modelling approach without any adjustments	9,228	0.385	60
4 × 4	Straightforward 2D modelling approach without any adjustments	3,098	0.561	11.3
4 × 4	A method based on adjusted conveyance and storage characteristics	9,067	0.393	12.9
6 × 6	A method based on adjusted conveyance and storage characteristics	9,031	0.388	9.2
8 × 8	A method based on adjusted conveyance and storage characteristics	8,798	0.375	1.3
10 × 10	A method based on adjusted conveyance and storage characteristics	8,046	0.423	0.75
12 × 12	A method based on adjusted conveyance and storage characteristics	7,949	0.428	0.60

and storage characteristics increased the computational time compared to straightforward model only marginally (12.9 min compared to 11.3 min). Therefore, the proposed method is a cost-effective way at achieving results close to a high resolution model by using a coarse grid model.

CONCLUSIONS

Several approaches to capturing key surface features in urban floodplains are reviewed in this paper. Particular emphasis was given to the use of coarse grid resolutions in 2D non-inertia models for which the new method was presented and corresponding case study results outlined. These results suggest that, when using coarser grid resolutions a special care needs to be given to the choice of the 2D modelling technique which needs to be employed in the related work. An important message is that the straightforward 2D modelling technique when applied to the coarse resolution of terrain data has a serious limitation in predicting the flow phenomena. The case study work presented in this paper demonstrates the weakness of such modelling technique in reducing simulation accuracy dependence upon grid resolution. On the other hand, the originally developed approach proposed and tested in this paper based on the volume-depth and area of flow-depth relationships derived from the high resolution topographic data has shown its capability of reducing simulation dependence upon grid resolution and producing results that are reasonably close to the results obtained from higher resolution models.

The same method also demonstrates its capability of shortening the simulation time while preserving the effects of small scale urban features. This point raises the possibilities of the present method to be used in optimisation and real time flood warning applications as such applications usually require an extensive number of simulations over a limited period of time.

Certainly, the present paper does not suggest inferring universal rules from a relatively limited case study work. However, the authors believe that the conclusions of the present study can be generalized to situations that have similarities with the present one, that is situations where the predominant phenomenon is overland flow (as it is the case with the case study work presented in this paper), and if it is represented relatively accurately by the sets of equations solved by the 2D non-inertia model and verified on the ground. Therefore, this type of approach demonstrates the possibility of applying a 2D non-inertia model more effectively in urban flood modelling applications whilst still making use of the high resolution of topographic data that can nowadays be easily acquired.

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