Effects of model schematisation, geometry and parameter values on urban flood modelling

ABSTRACT

One-dimensional (1D) hydrodynamic models have been used as a standard industry practice for urban flood modelling work for many years. More recently, however, model formulations have included a 1D representation of the main channels and a 2D representation of the floodplains. Since the physical process of describing exchanges of flows with the floodplains can be represented in different ways, the predictive capability of different modelling approaches can also vary. The present paper explores effects of some of the issues that concern urban flood modelling work. Impacts from applying different model schematisation, geometry and parameter values were investigated. The study has mainly focussed on exploring how different Digital Terrain Model (DTM) resolution, presence of different features on DTM such as roads and building structures and different friction coefficients affect the simulation results. Practical implications of these issues are analysed and illustrated in a case study from St Maarten, N.A. The results from this study aim to provide users of numerical models with information that can be used in the analyses of flooding processes in urban areas.

Key words | 1D-2D modelling, DTM resolution, model parameters, terrain features, urban flood modelling

INTRODUCTION

Urban flooding is a prominent issue, not only at a local scale but even more so at the global level. As of 2008, more than half the world’s population is living in urban conglomerations, many of which are situated at locations where large river systems meet the ocean. Hence, these megacities in delta areas are quite naturally exposed to flood events coming from either direction: inland or ocean (Talukdar 2006).

With respect to stormwater management practice and work that concerns studies which often involve flood risk analyses, one of the major aspects of such studies is the quantification of flood hazards and damage costs across the floodplain. The evaluation of risk due to flooding in urban areas similarly requires a detailed assessment of the potential risks that are possible (see Mark & Parkinson 2005; Teng et al. 2005). Physically-based computational modelling is invaluable for this purpose. With instantiated models, it is possible to explore the generation of floods and to simulate the effects in response to any control actions.

Physically-based models which are typically used in the urban flood modelling practice describe the system functioning in terms of processes that are accounted for by laws expressing general principles (i.e., continuity, momentum and energy conservation) and their reliability increases with the amount of measurement data that can be used for their instantiation and calibration. Over the past decade a one-dimensional (1D) approach has been used as a standard industry practice for quite some time. With the advances in computer power, fully integrated 1D-2D approaches have been receiving greater attention. Consequently there are still many researchers and practitioners who favour the use of 1D
modelling approach over other approaches. Some of the reasons are that these models are relatively easy to set up, calibrate and explain.

Where flood flows are confined to well-defined conduits, a robust 1D model can usually be instantiated and typically, within the range of the available calibration data, its results can be considered safe for decision-making. However, the flows generated along urban floodplains are normally highly complex because the morphology of the urban surface is predominantly artificial, with correspondingly highly irregular geometries, and may run contrary to natural flow paths. Modelling of flows in such complex geometrical situations is difficult. Small geometric 'discontinuities' such as road or pavement curbs can play a significant role in diverting the shallow flows that are generated along roads, through fences and around buildings. Head losses due to flows over or around such structures are particularly difficult to represent and accommodate in a detailed and exact manner. Furthermore, the urban flows can be supercritical, whereas many of the available modelling products, although they simulate flows that are in reality supercritical, in practice use modified subcritical flow algorithms. The use of finite difference methods in conjunction with the reduced momentum equation together with the boundary condition structure inherent in subcritical flow representations is a standard approach used for numerical simulation of all flow regimes (i.e., subcritical, supercritical and transcritical) in most of the commercial packages. Due to incomplete equations and the inadequate boundary conditions used to model supercritical and transcritical flows, such an approach may introduce unrealistic backwater effects, non-amplifying oscillations and other computational instabilities (Djordjevic et al. 2005). There is also the issue of treating the transition from channel flows to overground shallow-depth flows. All these issues necessitate the coupling of simulations using 1D and 2D modelling systems; see, for example, Hsu et al. (2000), Mark et al. (2004), Djordjevic et al. (2005), Chen et al. (2009), and Vojinovic et al. (2006). In Hunter et al. 2008, the benchmark testing of six two-dimensional (2D) hydraulic models (namely, DIVAST, DIVASTTVD, TUFLOW, JFLOW, TRENT and LISFLOOD-FP) with respect to their ability to simulate surface flows in a densely urbanised area has been carried out. One of the main conclusions from that study was that, while all the models tested produce plausible results, subtle differences between particular groups of codes give considerable insight into both the practice and science of urban hydraulic modelling.

The work described in this paper attempts to investigate how different DTM resolution, presence of different features on DTM (roads and building structures) and different friction coefficients affect the simulation results of urban flood models. Practical implications of these issues are analysed and illustrated in a case study from St Maarten, N.A.

1D and 2D Modelling

In 1D modelling, 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 and Tutulic 2009):

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = F_s 
\]

(1)

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

(2)

where $h$ is the water depth, $Q$ is the discharge, $\beta$ 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.

Typically, the boundary conditions are either discharges or water levels (or the equivalent depths) at conduit/channel ends. In a channel network, these are not known in advance and typically they are determined by the numerical solution procedure. The solution is commonly based on a temporary elimination of variables at internal cross-sections and reduction of all equations to a system of unknown water levels. In situations when transcritical flow conditions are possible, the approach proposed by Havno et al. (1985), which has proved to be numerically efficient, is applied. In this approach, the use of a standard implicit finite difference method is applied in conjunction with a gradual reduction of the inertia term in the momentum equation as the flow approaches critical conditions. Also, the algorithmic structure appropriate to subcritical boundary flow conditions (one boundary condition at each channel/conduit end) is applied. Even though the flow in a channel (or a conduit) might be supercritical, in which case it would need two boundary conditions at the upstream end and none at the downstream end, or, in a case of a hydraulic jump, where another boundary condition is required at the downstream end, the algorithmic structure of subcritical boundary conditions is still applied. This approach has been implemented in some of the key commercial software packages of hydraulic laboratories such as Wallingford.
averaged velocities, where \( \mathbf{s} \)

\[ \frac{\partial s}{\partial t} + \frac{\partial U}{\partial x} Uh + \frac{\partial V}{\partial y} Vh = F_s \]  \hspace{1cm} (3)

\[ \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + \frac{g}{C^2 d} \frac{\partial s}{\partial x} U \sqrt{U^2 + V^2} + \frac{\partial}{\partial x} \left( K_{xx} \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial U}{\partial y} \right) = F_U U_s \]  \hspace{1cm} (4)

\[ \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + \frac{g}{C^2 d} \frac{\partial s}{\partial y} V \sqrt{U^2 + V^2} + \frac{\partial}{\partial x} \left( K_{xx} \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial V}{\partial y} \right) = F_V V_s \]  \hspace{1cm} (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.

The simulation process in the case of coupled 1D-2D modelling is rather complex and it can become computationally very expensive. It is based on complex numerical solution schemes for 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 conditions (e.g., resistance coefficients, etc.) and bathymetry (as provided by a digital terrain model of the catchment area).

In urban flood-modelling applications, 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. Digital Terrain Models (DTMs) created from LiDAR (Light Detection and Ranging) data are utilised for that purpose. Such data can be processed to represent either the land surface alone (Figure 1a), land surface with the road network (Figure 1b) or land surface together with the road network and buildings (Figure 1c). For the first and second case (Figure 1a and b), since the buildings are represented as hollow objects, different land use areas are parameterised by means of different hydraulic friction coefficients, whereas in the third case (Figure 1c) buildings are represented as solid objects.

In the present paper, only schematisations presented in Figure 1a and b were employed in the experimental work.

**METHOD**

For this work, the 1D-2D coupled modelling approach was adopted for a case study of Cul De Sac catchment area, St Maarten, N.A (see also Vojinovic & Tutulic 2009). The land elevations range from near sea level at the southern end to 380 metre above mean sea level along the northern hilly part of the catchment. The drainage network contains lined and natural channels, natural waterways and roads, which combine to convey the storm water runoff in the absence of

**Figure 1** Schematisation of flow vectors in urban areas (Vojinovic & Tutulic 2009): 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).
properly engineered channels. The land use is mainly residential with some minor commercial buildings. The drainage channel network data was used to set up the 1D model. The floodplain flows were modelled with the 2D model. The DTM along the channel network, providing the interface between the coupled 1D-2D models, was set to the bank-full level of the 1D model. Several models were set for the experimental work, Table 1. Commercial software MIKE11 and MIKE21 were utilised.

The models were run for 100 year ARI event (with the total depth of 100 mm and duration of 1h).

The calculated subcatchment discharges are introduced as lateral or concentrated inflows into the branches of the model network. The hydrographs generated for each subcatchment were calculated using the unit hydrograph method (UHM). The method used for calculation of depths of the excess precipitation that contributes to runoff is the U.S. Soil Conservation Service (SCS) method. The time of concentration has been calculated using the Kirpich formula. The curve number applied to each subcatchment was identified on the basis of land use, type of the soil and percentage of imperviousness.

The friction coefficient used throughout the channel network of the 1D model was based upon the Manning’s M friction value of 30 (this value was estimated from the field records). For coupled 1D-2D model, due to the different channel and floodplain characteristics, different friction coefficients of 30 and 20 were used for the channel and the floodplain respectively. The basis for using Manning’s M value of 20 for the floodplain is to account for many complexities and obstructions that are present in the study area (e.g., fences, backyards, cars, trees, etc). In the 2D model applied here, Manning numbers are converted to Chezy numbers on the basis of the calculated water depth. The relationship used is:

$$C = Mh^{1/3}$$.

The units of Chezy numbers and Manning numbers are respectively m$^{1/2}$/s and m$^{1/3}$/s.

For stability reasons, the coupled 1D-2D model was run with the time step of 1 second and flooding and drying depths were set to 0.002 m and 0.003 m respectively.

Several models were built, taking into account different schematisation, geometry and parameter value characteristics. Table 1 describes the structure of 12 models employed in the present work.

## RESULTS AND DISCUSSION

From the experimental work described above, the following observations were made. For terrain which has a steep configuration and irregular geometry, such as the terrain in the Cul De Sac catchment on St. Maarten, the choice for a particular model formulation for floodplain analysis would

<table>
<thead>
<tr>
<th>Model</th>
<th>2D Model resolution</th>
<th>Manning’s M</th>
<th>2D model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 m</td>
<td>20</td>
<td>No building and road features</td>
</tr>
<tr>
<td>2</td>
<td>10 m</td>
<td>20</td>
<td>No building and road features</td>
</tr>
<tr>
<td>3</td>
<td>15 m</td>
<td>20</td>
<td>No building and road features</td>
</tr>
<tr>
<td>4</td>
<td>5 m</td>
<td>30</td>
<td>No building and road features</td>
</tr>
<tr>
<td>5</td>
<td>10 m</td>
<td>30</td>
<td>No building and road features</td>
</tr>
<tr>
<td>6</td>
<td>15 m</td>
<td>30</td>
<td>No building and road features</td>
</tr>
<tr>
<td>7</td>
<td>5 m</td>
<td>20</td>
<td>Building and road features included</td>
</tr>
<tr>
<td>8</td>
<td>10 m</td>
<td>20</td>
<td>Building and road features included</td>
</tr>
<tr>
<td>9</td>
<td>15 m</td>
<td>20</td>
<td>Building and road features included</td>
</tr>
<tr>
<td>10</td>
<td>5 m</td>
<td>30</td>
<td>Building and road features included</td>
</tr>
<tr>
<td>11</td>
<td>10 m</td>
<td>30</td>
<td>Building and road features included</td>
</tr>
<tr>
<td>12</td>
<td>15 m</td>
<td>30</td>
<td>Building and road features included</td>
</tr>
</tbody>
</table>
require careful consideration of the terrain characteristics and level of model details. Application of different DTM resolutions has made an impact on 2D models to produce results with the difference of up to 30% with respect to water levels and velocities. This was observed for simulations where building and road features were not incorporated explicitly in the 2D model domain (i.e., results from Models 1 to 6 in Table 1). In general terms, it was found that the lower DTM resolution tends to cause a wider spread of flood water with shallower depths when compared to the higher DTM resolution where the flood water tends to get confined to the local depressions, thus resulting in higher depths (Figure 2). Furthermore, by introducing buildings and roads into the DTM (Models 7 to 12, Table 1), even larger difference in water depths was observed (up to 50% in some locations).

The change in friction coefficients from 20 to 30 along the flood plain resulted in difference of model results up to 5%. The overall analysis indicates that the predominant factor for difference in results in the present experimental work is seen to be the resolution of a DTM data set. Also, the second influential factor is the incorporation of terrain features. When the two factors were combined together then the largest difference was observed. This implies that the accurate description of urban conditions which contains complex geometrical features is a critical factor in determining success of the flood modelling work. Small geometric ‘discontinuities’ such as road or pavement curbs can play a significant role in diverting the shallow flows that are generated along roads, through fences and around buildings and as such they must be adequately taken into account.

Comparatively, the difference in friction parameter values has caused much less influence on the simulation results. This implies that in some cases model calibration (that consists of fitting the simulation results to the measurements by adjusting the parameter values) can be meaningless if the geometrical features and terrain characteristics are not adequately captured by the 2D model in the first place. In such case, a modeller should be able to explain the difference between the modelled and observed data and suggest if any further adjustment should be done. To better express the confidence of model results, it is a valid comment to mention that all model results should be provided with an uncertainty level.

Certainly, the work presented in this paper does not suggest inferring universal rules from a limited modelling experiment. However, we do believe that the conclusions drawn from this study can be generalised to those catchments which have similar characteristics. A point of crucial importance here is that DTMs should never be taken blindly without prior verification. The study suggests a fundamental precaution to check whether terrain features such as local depressions, pits and other geometric ‘discontinuities’ are adequately captured by the DTM and whether they

---

**Figure 2** | Computed water depths for 5 m (top left image), 10 m (top right image) and 15 m (bottom image) DTM resolution.
correspond to actual physical reality. Furthermore, such issues should dictate the desired resolution of a DTM for a particular case study.

It is also interesting to note that the 1D-2D coupled models used in this work needed almost 2 h for a single event simulation on Pentium D machine with 1 GB of RAM memory.

CONCLUSION

From the work presented here, it can be concluded that successful application of coupled 1D and 2D models greatly depends on the DTM resolution. The paper demonstrates that the phenomena occurring on the catchment and the terrain topography are factors that could make for substantial differences between the results obtained from models with different level of details. This implies also that the requirements for a DTM resolution must involve careful consideration of the geometrical features of the area under study and the objectives of the work. On the one hand, coarse resolution of a DTM is likely to cause unrealistic results as the influence of buildings cannot be represented adequately (and therefore adjustment of friction coefficients across the terrain would remain as a last resort to tackle this issue), but on the other hand, very fine resolution would make simulation last very long due to the need for significant lowering of simulation timesteps. The influence of different friction coefficients was found to be not as significant as that of the model geometry or schematisation.

REFERENCES


<table>
<thead>
<tr>
<th>Location</th>
<th>Resolution</th>
<th>5 m</th>
<th>10 m</th>
<th>15 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.0</td>
<td>0.85</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.85</td>
<td>0.85</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.70</td>
<td>0.65</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>0.0</td>
<td>0.20</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0.0</td>
<td>0.0</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>