Urban drainage models for flood forecasting: 1D/1D, 1D/2D and hybrid models

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Abstract

Lead time between rainfall prediction results and flood prediction results obtained by hydraulic simulations is one of the crucial factors in the implementation of real-time flood forecasting systems. Therefore, hydraulic simulation times must be as short as possible, with sufficient spatial and temporal flood distribution modelling accuracy. This paper presents hybrid models, a new type of models in which the 1D/1D and the 1D/2D approaches are combined together in order to take advantage of their benefits and overcome their drawbacks.

The models used in this paper comprise a sewer network and an overland flow drainage system in both 1D/1D and 1D/2D approaches. The 1D/1D model is used as the reference model to generate several models. The results presented in this paper suggest that the 1D/2D models are not yet suitable to be used in real-time flood prediction applications due to long simulation time, while on the other hand, the hybrid models show that considerable reductions in simulation time can be achieved without compromising simulation results (flow and water depth) accuracy.

Keywords

Urban drainage models; hybrid models; pluvial flooding; surface flooding; flood forecasting

Introduction

Flooding in urban areas is occurring with increasing frequency all over the world and is causing repeated damage that calls for improved management of floods from all sources. According to the UK Government’s Independent Review into the Summer 2007 Flood Event (Pitt Review, 2007), about two thirds of flood damage in urban areas was caused by surface water (pluvial) flooding. While fluvial and coastal floods are well documented with extensive fluvial flood mapping and fluvial flood warning systems in place, this is not the case for surface water flooding. Furthermore, the time scales of fluvial and coastal flooding allows for timely flood warning response. As opposed to this, surface water flooding caused by intense local storms during which the capacity of the sewer network and of the surface drainage system is often exceeded takes place at smaller temporal and spatial scales and has, until recently, not been given appropriate attention; forecasting such events is still in its “infancy”. There is not yet reliable industrially accepted method for this type of forecast.
To minimise this damage, it is necessary to accurately and timely predict the spatial and temporal distribution of these events. The dual-drainage concept (Djordjevic et al. 2004) has been implemented in several research and consultancy urban drainage projects. It consists of a network of open channels and ponds (major system) connected to the sewer system (minor system). Initially, one-dimensional sewer and surface modelling was introduced (1D/1D approach), but recently a more complex model has been tested with one-dimensional sewer model and two-dimensional surface model (1D/2D) (Djordjevic et al., 2007; Allitt et al., 2009). In both cases the sewer network model is coupled with the overland (surface) flow model.

The Urban Water Research Group (UWRG) of Imperial College London has worked on the development of the Automatic Overland Flow Delineation tool (AOFD). The AOFD is a tool that contains several GIS-based routines that automatically analyse, quantify and generate a one-dimensional overland flow network model (consisting of ponds and flow pathways); the resulting model can be coupled with the sewer network model in order to simulate and forecast pluvial flooding. The AOFD tool analyses several GIS layers such as Digital Elevation Model (DEM), land uses (buildings, streets, green areas) layers, etc. (Maksimovic et al. 2009, Leitão 2009).

Given that pluvial flooding happens quickly (urban areas can be flooded in 10 to 20 minutes when heavy rainfall occurs), it is essential to have hydraulic models capable of estimating these events fast enough, so that longer lead time is available and operational responses can be timely triggered in order to minimise damage and vulnerability. Although the sophisticated 1D/2D models are very detailed and accurate, their run-time is too long for real-time applications (Leitão et al., 2010). On the contrary, 1D/1D models are fast and therefore more suitable for real-time purposes; however, they are less detailed and accurate. (Leitão et al, 2010, Simões et al, 2010)

This paper presents a new type of models in which the 1D/1D and the 1D/2D approaches are combined together in order to take advantage of their benefits and overcome their drawbacks. Several tests are performed using the 1D/1D, 1D/2D and hybrid models with different levels of 1D and 2D areas on the overland network. 1D/1D concept is applied in most of the catchment whereas 1D/2D concept is applied in areas where critical flooding usually occurs. This paper presents the comparison of the results obtained using the different models, namely in terms of water depth in the flooded areas, flood extent and time required to run the models. With the results obtained from this research, it will then be possible to assess the effectiveness of the different models. Two case study areas were chosen to perform the tests: the Canbrook catchment in London (United Kingdom) (Portugal).

METHODOLOGY

The Urban Water Research Group (UWRG) of Imperial College London is currently developing new techniques and methodologies for modelling and predicting (in real time) pluvial flooding. These techniques are being implemented and tested in the Cranbrook catchment, which is located within the London Borough of Redbridge (situated on the northeast part of Greater London). The CranBrook is a tributary of the Roding River and, in turn, the Roding River is a tributary of the river Thames. In what follows, the new models and methodologies that are being developed at the UWRG, as well as its implementation in the Cranbrook case study are briefly explained. For such modelling, use is being made of
Infoworks CS and RS, along with the AOFD (Automatic Overland Flow Delineation) “tool” developed by UWRG (Maksimovic et al., 2009).

The approach developed by the UWRG includes two modules: (1) short term rainfall analysis and prediction and (2) short term flood prediction. In order to accurately and timely model and predict surface water flooding, these two models need to be coupled together.

Regarding the first module, it has to be taken into account that modelling of urban pluvial flooding requires short term rainfall prediction with high spatial and temporal resolutions. The state-of-the-art methods for high-resolution rainfall prediction/modelling are mainly based upon radar nowcasting techniques; however, the lead time of these methods (approximately 15 – 60 minutes) is insufficient for the corresponding surface flood models to carry out an accurate and timely flood estimation. To overcome these shortcomings, an integrated methodology consisting of rainfall models and observation techniques over multiple spatial and temporal scales is currently under development at the UWRG of Imperial College London in cooperation with MetOffice. The aim of the techniques that are being developed is to increase the lead-time of the rainfall forecast as well as to improve its resolution, accuracy and reliability.

With respect to the second module (short term flood prediction), in order to reliably model urban pluvial flooding, it is necessary to realistically represent the urban fabric in its complexity, to take into account the interaction between the overland and sewer networks, as well as the boundary conditions that determine the performance of the system. With this purpose, 1D/1D Infoworks models of the overland and sewer networks of the study area are being developed. It is worth mentioning that the computational time required to run these models is a key factor, given that the models are intended to be used for Real Time forecasting. For this reason, 2D overland models would not be suitable for this purpose. To develop the 1D surface network, a special tool called AOFD tool was developed at the UWRG; the AOFD tool uses a high-resolution DTM (Digital Terrain Model), obtained from 1 m resolution LiDAR data) for creation of the network of ponds and preferential pathways that connect them. The output of the AOFD software is an Infoworks 1D model that can be easily coupled with the sewer network model (the connection between these two systems takes place at the manholes).

After setting up the Infoworks models, they need to be fed with rainfall forecast data (produced with the above mentioned techniques), in order to produce flood forecasting. To do this, a special tool that converts radar format rainfall data into a format that can be directly fed to Infoworks RS and CS was developed at the UWRG.

The developed models are now being calibrated and tested using historical data as well as real time data obtained from a monitoring system that was implemented in the study area (Figure 1). The monitoring system includes three tipping bucket rain gauges, one pressure sensor for Roding river level monitoring, two sensors for water depth measurement in sewers and one sensor for water depth measurement in open channels. All of these sensors are equipped with data acquisition and wireless communication units, so the information collected with it can be accessed in real time via Internet.
Case Study: The Cranbrook Catchment
The case study used for testing the performance of the different hydraulic models is the Cranbrook catchment. This catchment is located within the London Borough of Redbridge, which is situated in the Northeast part of Greater London (close to the 2012 Olympic site).

The Cranbrook is a small tributary of the Roding River, which, in turn, is a tributary of the Thames (Figure 1). The Roding River constitutes a boundary condition for the overland and sewer networks of the Cranbrook catchment, given that the water levels in the Roding River (when at high stage) affect the capacity of the sewers and open channels of the Cranbrook catchment, creating a “backwater” effect.

The Cranbrook catchment is predominantly urban and has a drainage area of approximately 900 hectares; the main water course is about 5.75 km long, of which 5.69 km are piped or culverted. According to EA (2006), this area has a rapid response to rainfall, which is typical of densely urbanised catchments overlying London clay. Furthermore, this area has experienced several pluvial, fluvial and coincidental flooding in the past, with the most recent events being in 2000 and 2009, when hundreds of properties were flooded. These flood events are relatively well documented and can be used for development of advanced flood prediction methodologies.

![Legend](image1)

**Figure 1.** Cranbrook catchment. (a) location of Cranbrook catchment in relation to the Roding River catchment; (b) Cranbrook catchment; (d) monitoring system installed in the study area.
HYDRAULIC MODELS
Three different type of physically based models were implemented

1D/1D Models
The 1D/1D model was created by employing the storage nodes and overland flow paths delineated using the AOFD methodology (Maksimovic et al. 2009). A LiDAR (Light Detection And Ranging) DEM with cell size 1x1m and vertical accuracy of approximately 0.15m was used in the delineation. The cross-sections of the overland flow paths were confined to open rectangular or open trapezoidal channels. The 1D/1D model was then set up by coupling the sewer network and the 1D overland flow network.

1D/2D Models
The 1D/2D model used in this study was created using the Infoworks CS 2D module (Wallingford Software 2009). The model comprises a 1D sewer network linked to a 2D surface which represents the terrain. The 2D surface was generated from the same LiDAR DEM used to generate the 1D overland flow network of the 1D/1D model. The 2D mesh (surface) resolution was created with the following parameters: 1,000m² maximum triangle area and 250m² minimum mesh element area.

Hybrid Models
The hybrid models are physically based models that have a 1D overland network and a 2D overland network in most affected areas. Traditionally if the 2D domain does not extend to all the study area the information in the overland network is lost. With the hybrid models it is possible to have overland network information in all the catchment with a faster model. Figure 2 shows the interactions between the 1D overland network and the 2D mesh. The most vulnerable area has a 2D mesh where the flood is simulated and the transition between the 1D and 2D overland network is made in the downstream node of the 1D overland pathway that crosses the 2D boundary. The water goes from the 1D overland network to the 2D mesh and vice-versa through a 2D outfall (Infoworks CS feature). (Figure 2)

RESULTS
Three different models were used in this study and three designed rainfall events were used (Flood Estimation Handbook). The analysis of the results is focused on simulation time required to run the simulations and quality of the results obtained.

Figure 3 shows the inflow from the overland network into the sewer network, the flow in pipe 1431.1, water level in the downstream node of that pipe (upstream the 2D area) for the 30 yr
return period rainfall event. The pipe and manhole are in an area in which the hybrid model is 1D. This emphasis the need of having an overland network all over the study area. As expected, the 1D/1D model and Hybrid model have the same results in this area.

![Graphs showing simulation results](image1)

**Figure 2:** Simulation results in pipe 1431.1 and its downstream node: a) Inflow from the overland network and sewer system; b) Flow in the pipe; c) water level in the downstream node

The Figure 3 shows the water depths in the 1D/1D and 1D/2D models for the 200yr return period rainfall event. The 1D/1D shows the pond delineation. The water depth in the 2D mesh of both hybrid and 1D/2D model are very similar (slightly higher water depths in 1D/2D that can be explained by lower retention capacity of this model).

![Graphs showing water depths](image2)

**Figure 3:** Flood extend in: a) 1D/1D network; b) Hybrid network; c) 2D model

Figure 4 shows the water level and flow in pipe 463.1 (downstream the 2D area). In all models the results are very similar.
Figure 4: Simulation results in pipe 1431.1 and its downstream node: a) Inflow from the overland network and sewer system; b) Flow in the pipe; c) Water level in the downstream node.

As can be seen in Table 1, the great advantage of 1D/1D models is the run time of simulation, which makes it more suitable for flood forecast. Table 1 shows the simulation time for several different rainfalls. As expected the 1D/1D is much faster than the 1D/2D, however the hybrid model is also very fast. It is slightly slower than the 1D/1D and it has results similar to the 1D/2D model. In all models the simulation time increases with the return period of the rainfall event but the results suggest that the 1D1D model is more sensitive to this aspect (the relative time difference is lower for high rainfall events).

Table 1: Time of simulation for the three models and the three storms, and comparison of their simulation time with the 1D/1D model simulation time

<table>
<thead>
<tr>
<th>event duration</th>
<th>model</th>
<th>Simulation time [hh:mm:ss]</th>
<th>Difference to 1D/1D</th>
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<tr>
<td>30 yr return period 300 min</td>
<td>1D/1D</td>
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<td>+156%</td>
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<tr>
<td></td>
<td>1D/2D</td>
<td>00:45:23</td>
<td>+2469%</td>
</tr>
<tr>
<td>100 yr return period 300 min</td>
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<td>00:02:11</td>
<td></td>
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<tr>
<td></td>
<td>Hybrid</td>
<td>00:05:20</td>
<td>+144%</td>
</tr>
<tr>
<td></td>
<td>1D/2D</td>
<td>01:11:10</td>
<td>+3160%</td>
</tr>
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<td>200 yr return period 300 min</td>
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<td>+25%</td>
</tr>
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<td></td>
<td>1D/2D</td>
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<td>+1530%</td>
</tr>
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</table>

DISCUSSION AND CONCLUSIONS

1D/2D model is more detailed and in some cases more accurate than 1D/1D (Mark et al, 2004). However the simulation time is not suitable for real time flood forecast. In order to overlap this drawback a new type of model was presented. It combines 1D overland network with a 2D overland network which allows to have 2D simulation in the most critical areas, with a fast simulation time and without losing information in other areas that also flood. The new model shows a good agreement with the 1D/2D model and the simulation time is similar with the 1D/1D which makes it also suitable for flood forecasting.
Future work in the calibration between the elements that connect the 1D sewer network and the overland network and between the 1D overland network with the 2D mesh is still required.

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