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<td>Albert S. Chen, Michael Hammond, Justine Hénonin, Nina Donna Sto. Domingo</td>
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SUMMARY
We reviewed different approaches for urban flood modelling. The data requirement, available information, adequate scale and applications of these approaches are also compared. A recommendation for selecting appropriate models for simulations is also suggested. The CORFU framework has been developed to evaluate the urban flood risk affected by the external drivers including climate change, urban growth and social-economic changes. The framework can be applied to estimate the effectiveness of resilience measures in a city scale to help strategic planning.
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1 Introduction

Urbanisation associated with economic growth, particularly in developing countries, has become an inevitable fact of progress in the past half century (United Nations, 2010). Nowadays, more than 50% of the world’s population lives in urban areas. This trend is rising and it is estimated that nearly 69% world population will be living in urban areas by 2050. Hazard risks and exposures increase rapidly in cities (Mitchell, 2003), as a consequence of the concentration of population and wealth, exhaustion of resources, and changing environmental and human activities.

The IPCC’s Fifth Assessment Report (IPCC WGI, 2013) concludes that global warming is unequivocal from observations of various indices. Extreme weather events such as floods, heat waves and droughts are projected to be more frequent and intense over the 21st century. The Stern Report on the Economics of Climate Change (Stern, 2007) identifies that even if we could stop all greenhouse gas emissions tomorrow our climate would continue to change due to global warming driven by over a century of manmade emissions. As a consequence, the risk of extreme weather events is likely to continue increasing over the next half century and today’s weather extremes are likely to become tomorrow’s norms.

The last ten years have witnessed a large number of serious flood events around the world due to the changing climate (Goswami et al., 2006). In Europe alone, more than hundred severe floods have led to nearly one thousand deaths, displacement of more than half a million people and damage and economic losses that amount to tens of billions of Euros. In addition, projections of future climate changes and of external and internal urban growth indicate that flood risks will be exacerbated in many regions. Consequently, governments, policy makers and communities worldwide have been forced to review their flood management strategies and invest more resources in portfolios of structural and non-structural measures. The European Directive on the Assessment and Management of Flood Risks (2007/60/EC of 23 October 2007) (the Floods Directive) and the wider EU Flood Action Programme call for improved flood forecasting and early warning systems as well as for flood risk mapping.

This report will review the existing methodologies and tools for urban flood modelling and flood hazard mapping to propose a consistent framework for urban flood risk modelling. These methodologies range from simple conceptual lumped models to urban flood models describing the full hydrological cycle including flow in the sewer system. A clarification of the relevant scales and methodologies for urban flood analyses associated with the choice of urban flood model will be carried out, including analyses of required resolution and level of detail in data about terrain, land-use, sewer network and structures, adequate for different scales (micro/mezzo/macro) aiming at urban flood models fit for the purpose, such as: mitigation planning, emergency plans and RT forecasts.

2 Category of urban flood modelling

Approaches to the simulation of urban flooding have evolved significantly in recent years.
2.1 Hydrological modelling

Hydrological models have been widely applied, using simplified lumped parameters, to calculate the surface runoff at outlets of sub-catchments or in river channels. Flooding is assumed to occur when the flood volume exceeds a pre-defined threshold or the discharge is greater than the capacity of a channel. A water spreading model is then adopted to fill the adjacent flood plains to determine the flood extent (Lhomme et al., 2008; Liu and Pender, 2012). This approach requires little computational resources, comparing to hydraulic modelling, such that it can provide an overview of the hotspots that are at risk of flooding with restricted lead time. Therefore, it is widely applied to real time flood forecasting such as Hvidovre system in Denmark (Hénonin et al., 2013) and Grid-to-Grid in England (Price et al., 2012).

![Image of runoff computation results from hydrological modelling](image)

**Figure 2.1** Example of runoff computation results from hydrological modelling. (Source: Henonin et al., 2013)

2.2 1D modelling

Many 1D hydraulic models (e.g. HEC-RAS, Brunner, 2002; SWMM, Rossman, 2010) were developed for the design of sewer network or flood defence systems such that their applications often simplify the situation when the flow in the system exceeds the design standard. They often treat floodwater as a stagnant volume stored temporarily in a virtual reservoir above a sewer system manhole or a floodplain next to the channel, from which water starts returning when the conditions permit due to the hydraulic head in the node falling below the ground level. With this simplified approach, the only measure of the severity of flooding is the volume of flood water at individual nodes, whereas spatial extent, duration, flood depths and velocities remain unknown. In this case, the above-mentioned flood spreading models or the pre-defined flood volume-area or the volume-depth curves are often associated to determine the extent or depth of flooding.
2.3 2D modelling

To simulate detailed flood propagation on the ground surface, many physical-based 2D flood models solve the shallow water equations (SWEs) have been developed. However, the 2D flood models require huge computational resources to solve the SWEs such that efforts been attempted to improve the modelling performance, while maintaining accuracy, by reducing the complexity of the SWEs. This reduction is usually achieved by approximating or reducing the term of the equations (Hunter et al., 2007). JFLOW model (Bradbrook et al., 2004), Urban Inundation Model (UIM) (Chen et al., 2007b), and the diffusive version of LISFLOOD-FP (Bates and De Roo, 2000) solve the 2D diffusion wave equations that ignore the inertial term. Bates et al. (2010) included the acceleration inertial term into the LISFLOOD-FP and concluded that the additional term allows a stable time step that is 1–3 orders of magnitude greater than the ones used in the diffusive version, which speeded up the calculation significantly. Other recent studies show promising developments in the cellular automata approach for urban hydroinformatics (Dottori and Todini, 2013, 2011; Ghimire et al., 2013).
Some other models adopt multi resolution grid or irregular mesh grid (Innovyze, 2013) to achieve higher performance. Chen et al. (2012a, 2012b) represented the key micro-features in urban areas using building coverage ratio, conveyance reduction factor, and multiple layers in modelling to speed up the calculations. Hartnack et al. (2009) have shown that a 2D multicell solver could reduce model runtimes by a factor of up to 10. This multicell solver, available in a commercial package (MIKE 21; DHI, 2014a), combines a coarse hydraulic computation grid with a fine grid that contains topographical data. The fine grid resolution can be adapted to an urban context, showing potential for analysis at mega-city scale (Hénonin et al., 2013).

Figure 2.5 Computational grids used in 2D modelling. The left figure shows a regular grid, while the right figure shows a mesh.

Many of these physical models have been also updated to speed up the run time by parallelising the computation, thanks to the recent advance in parallel computing techniques and easy to access parallel capable hardware. For example, InfoWorks ICM (Innovyze, 2013), JFLOW-GPU (Lamb et al., 2009), and GPU-DASH (Smith et al., 2013) use the massive parallel computational power of the graphics processing units (GPUs) of modern graphics card to reduce the computation time. LISFLOOD-FP uses the OpenMP library (Neal et al., 2009) and the MPI library (Neal et al., 2010) to take advantage of multi-core CPUs. Other 2D models tested the possibility to share the computational work among remote distribute computers or the in Cloud like the FloodMap-Parallel model (Yu, 2010) and CityCAT urban flood model (Glennis et al., 2013). The Environment Agency has adopted JFlow+ 2D hydraulic model that utilises the computing power of GPU to generate the updated Flood Map for Surface Water (uFMfSW) for England and Wales (Environment Agency, 2013) on a 2m resolution grid. The function of sewer network was represented by the reduction to rainfall in the uFMfSW.

2.4 1D/1D modelling

A significant step forward was the dual drainage concept, where the urban surface is treated as a network of open channels and ponds (major system) connected to the sewer system (minor system). These systems are modelled using weir/orifice-type elements representing inlets/gullies and holes on manhole covers, through which a direct interaction between the two systems takes place (Mark et al., 2004). The runoff processes on overland are usually ignored in 1D modelling and inundations are often assumed caused by over bank floods from channels or surcharge of storm sewers. Inundation depths and extents are determined by using pre-defined stage-volume or stage-area functions. 1D numerical models that solve the Saint Venant equations are popular in hydraulic modelling for reasons of computational simplicity and ease of parameterisation (Horritt and Bates, 2001). The applications include simulations of the flood propagations along river channels
(Kazezyilmaz-Alhan and Medina, 2007; Pelletier et al., 2005), flow field analyses of hydraulic structures (Federico et al., 2003; Picek et al., 2007), flood impact assessments on habitants (Hammersmark et al., 2005; Sear and Newson, 2004), etc. Many commercial packages such as Infoworks (Innovyze, 2013) and MIKE 11 (DHI, 2014b) are applicable and popular in both academic researches and industrial practices.

Figure 2.6 Illustration of a 1D-1D model simulating flows over the street network and through the underground drainage system.

This approach allows for dynamic simulation of flood flow movement with the results in the form of hydrographs – local flood flow depths and velocities that can be used for analysing different flood mitigation schemes, damage evaluation, flood risk mapping etc. Some of the limitations of this method are inherent to its one-dimensional (1D/1D) nature (Djordjević et al., 2005). Research has been undertaken to enhance the potential of this type of model by more accurate GIS-based automatic generation of surface network characteristics such as pond stage-area curves, flow paths, cross-section geometry, connectivity, and roughness from DEM and land-use images (Blanksby et al., 2007). Experimental research in laboratory conditions has been conducted to improve knowledge about various local phenomena related to urban flood modelling, such as energy losses at street crossings (Riviere et al., 2005), time required for emergency evacuation from underground spaces (Ishigaki et al., 2008) and interactions between above and below ground flows through gully structures (Saul and Djordjević, 2009).

2.5 1D/2D modelling

1D models are incapable of describing details of such scenarios, therefore, 2D models are required for overland flow simulations. Therefore, 1D/1D dual drainage models have been superseded to a large extent (although not made redundant) by coupled 1D/2D models recently, in which a 1D sewer network model is coupled with a 2D surface flow model (Carr and Smith, 2006). Interactions between the two models take place between underground network nodes and surface computational grid cells. This approach enables more realistic analysis of overland flows than the 1D/1D approach, especially in extreme events in which flood flows are not confined to street/road profiles and where the exact treatment of buildings is required. However, 2D models typically require time steps much smaller than 1D models (depending on spatial resolution), so coupled 1D/2D urban flood modelling can be computationally demanding.
Hsu et al. (2002), Chen et al. (2007a) and Seyoum (2011) coupled the sewer and the overland flow models to simulate the bi-directional flow interaction between the sub-surface and the surface systems. Commercial software developers also provide various 2D modelling products that are coupled with 1D channel or 1D sewer models such as SOBEK (Deltares systems 2014), XP-SWMM 2D (Phillips et al. 2005), MIKE Urban (DHI Software 2014) and InfoWorks (Innovyze 2012).

3 Discussions

3.1 Selection of flood modelling method

Selection of the flood model to use from among the available methods, such as those described in Chapter 2, depends on several factors. These include:

- The purpose and objectives of the analysis
- The identified dominant flood processes and physical characteristics of the area
- The needed accuracy of required information/model output
- Data availability

The modelling exercise begins with defining the objectives of the analysis. The analysis could simply aim to determine whether flooding may occur, or it could also require information on where flooding may happen. In other cases there may be a need for detailed calculations of flood extents and levels for events with various return periods. The available flood modelling methods offer different types of information with their results, and thus certain methods may be selected depending on the types of information needed in the analysis.

The analysis is also given direction and focus through identification of the dominant processes involved in the phenomenon (i.e. flooding). This information narrows down the choices for an appropriate modelling method to be used in the analysis as different methods have different capacities for simulating flood-related processes. The selected model must be able to describe the dominant processes involved in the study. The dynamics in urban drainage system and terrain characteristics are usually important determinants for selecting modelling tools. For a simple urban drainage system where the system dynamics may be less important, a water balance analysis could be enough to calculate flood extents such that the application advanced (complex) physically-based models might be unnecessary.
The needed accuracy or level of detail in an analysis also plays a role in selecting the modelling method. The requirements of information must be adapted according to achieve a good balance among the time, the cost and the quality aspects of a project.

Finally, the level of detail and quality of data that are available for modelling is an important consideration in selecting the method to use. All models have different data requirements and the selected model must have sufficient (i.e. in terms of type and quantity) input data that can properly describe the processes being simulated. In addition, the collection and processing of the data must be feasible within the modelling project period. In addition to data needs, the availability of other types of resources (e.g. hardware, technical skills) for conducting the modelling exercise is an important consideration in selecting the type of model to be used in the analysis. Procurement of the software and hardware needed for the selected model must be possible, and furthermore, human skills needed to build, run, and understand the results and limitations of models must be available.

Figure 3.1 from the report ‘A Cookbook for Analysis of Climate Change Effects on Floods in Cities’ (DANVA, 2011) illustrates how various modelling tools are used depending on the application or objectives of a study. The figure may be considered as a summary of the above-mentioned various considerations when selecting a model for a modelling exercise. It takes the form of an odometer that shows a range of modelling methods (Technical Track) starting from the most basic (e.g. DTM (Digital Terrain Model) mapping) to the most complex (e.g. 1D-2D flood modelling) with a matching type of application (Application Track) deemed appropriate for each method. Relatively simple terrain models may, for example, be used by city planners for developing land use plans in relation to storm water management. But for river management, hydraulic models for rivers and terrain models may be required as details about water levels and discharge may be needed.

Table 1 summarises some of the main advantages and possible outputs of each modelling approach regarding urban flood applications. Hydrological, 1D and 1D/1D models are limited to provide detailed surface flood information unless heavy GIS post-processing is involved to translate the modelling results into flood depth and extent. Those converted information are less accurate and
less precise for micro scale case studies. The quick computing time enables their applications in real-time forecast, early warning and emergency operations.

On the contrast, 2D and 1D/2D models can produce detailed flood depth, velocity and extent information (maximum and temporal evolution), which allow better estimation of flood hazard and damage. The detailed information can help the authorities to set up strategies for hazard mitigation and emergency planning. However, more detailed models require longer computing time such that these models are less capable for real-time flood forecasting for macro or mezzo scale case studies. Applications have been developed to engage 2D or 1D/2D modelling results with real-time flood forecasting by associating offline simulated maps with real-time rainfall or radar information (Hénonin et al., 2013; Hsu et al., 2011).
### Table 1. Model potential for urban flood applications

<table>
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<th>1D model</th>
<th>2D model</th>
<th>1D/1D model</th>
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<td><strong>Main data requirement</strong></td>
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<td>Topographic data (DEM and/or DTM)</td>
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<td><strong>Drainage network representation</strong></td>
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<td>Simplified drainage capacity representation</td>
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<td>Real-time forecast Early warning, Emergency operation</td>
<td>Mitigation planning, Emergency planning</td>
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<td>Estimation of runoff distribution</td>
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<td>Flood extent Flood damages</td>
<td>Flood extent Flood damages</td>
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<td>Hotspots</td>
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3.3 Urban flood risk mapping framework

Within the CORFU project, we have developed a framework for urban flood modelling and risk assessment, which combines hydraulic modelling result and damage assessment tools. The hydraulic modelling can be in either micro, meso or macro scale, depending on the data availability and computing resources. The damage assessment tools can associate the modelled flood information with buildings, land-use, and vulnerability characteristics to evaluate the impact of flooding. The tools will refine the hydraulic modelling results to a finer resolution to make the best use of information. The tools are designed to cope with macro scale problems with a resolution of individual buildings. The flexibility allows the framework to cope with case studies with different scales and various data quality.

To consider the impact of future climate change, urban growth and social-economic changes, the CORFU framework can reflect the changes in hydraulic modelling and damage assessment. The results can be analysed and compared in terms of expected annual damage or resilience index. The effectiveness of resilience measures can be evaluated to before being employed. The combination of measures and their timing of implementing can therefore be developed to improve the flood resilience of cities.

4 Summary

We reviewed different approaches for urban flood modelling. The data requirement, available information, adequate scale and applications of these approaches are also compared. A recommendation for selecting appropriate model for simulations is also suggested. The CORFU framework has been developed to evaluate the urban flood risk affected by the external drivers including climate change, urban growth and social-economic changes. The framework can be applied to estimate the effectiveness of resilience measures in a city scale to help strategic planning.

5 References


Saul, A.J., Djordjević, S., 2009. FRMRC2 project, internal progress report on WP3.7 Improved understanding of the performance of local controls linking the above and below ground components of urban flood flows.


