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Evaluating the importance of catchment hydrological parameters for urban surface water flood modelling using a simple hydro-inundation model

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SUMMARY

The influence of catchment hydrological processes on urban flooding is often considered through river discharges at a source catchment outlet, negating the role of other upstream areas that may add to the flooding. Therefore, where multiple entry points exist at the urban upstream boundary, e.g. during extreme rainfall events when surface runoff dominates in the catchment, a hydro-inundation model becomes advantageous as it can integrate the hydrological processes with surface flow routing on the urban floodplain. This paper uses a hydro-inundation model (FloodMap-HydroInundation2D) to investigate the role of catchment hydrological parameters in urban surface water flooding. A scenario-based approach was undertaken and the June 2007 event occurred in Kingston upon Hull, UK was used as a baseline simulation, for which a good range of data is available. After model sensitivity analysis and calibration, simulations were designed, considering the improvement of both the urban and rural land drainage and storage capacities. Results suggest the model is sensitive to the key hydrological parameter soil hydraulic conductivity. Sensitivity to mesh resolution and roughness parameterisation also agrees with previous studies on fluvial flood modelling. Furthermore, the improvement of drainage and storage capacity in the upstream rural area is able to alleviate the extent and magnitude of flooding in the downstream urban area. Similarly urban drainage and storage upgrade may also reduce the risks of flooding on site, albeit to a less extent compared to rural improvements. However, none of the improvement scenarios could remove the flow propagation completely. This study highlights that in some settings, urban surface water flood modelling is just as strongly controlled by rural factors (e.g. infiltration rate and water storage) as internal model parameters such as roughness and mesh resolution. It serves as an important reminder to researchers simulating urban flooding that it is not just the internal parameterisation that is important, but also the use of correct inputs from outside the area of study, especially for catchments with a mixture of urban and rural areas.

1. Introduction

Flood risk managers and decision-makers often face the challenging tasks of designing effective mitigation and adaptation strategies in response to low-frequency and unexpected urban flooding arising from extreme storm events, during which, the combination of surface water runoff and storm sewer surcharge are the two major sources of inundation. Storm sewer flooding is due to the surcharge of excess water that cannot be drained by the sewer system and is therefore usually localized. The modelling of storm sewer induced urban flooding has seen a great body of literature in the last few decades, with a range of modelling approaches developed including the 'dual-drainage modelling' (1D/2D) (Djordjević et al., 1991; Hsu et al., 2000; Schmitt et al., 2004; Seyoum et al., 2012) and the 1D/1D approach (Mark et al., 2004). Such approaches typically couple: (i) the solution of the 1D shallow water equations for the storm sewer systems; and (ii) a 1D or 2D representation of surface flow. These approaches are able to provide a good estimate of urban flood risks at the local scale. The accuracy of the model predictions depends on a number of factors, including the accuracy of: (i) the topographic data; (ii) inflow to the drainage inlets, usually derived from hydrological estimation; and (iii) the geometries of the storm sewer pipes. In comparison, direct surface water runoff in urban environments are less well studied. Surface water flooding may arise from

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rainfall-generated overland flow before the runoff enters watercourses or is captured by the sewer system. It is usually associated with high intensity rainfall (e.g. >30 mm/h), during which urban storm sewer drainage systems and surface watercourses may be overwhelmed, preventing drainage through artificial (e.g. pumping) or natural means (e.g. gravity). Moreover, even when fully functioning, urban storm sewer systems may not have the capacity to capture all the surface runoff through inlets during extreme events and direct surface runoff can overpass manholes and accumulate to form ponding in topographic depressions due to inlet efficiency (Aronica and Lanza, 2005). In addition, surface water flooding can also originate from rural areas adjacent to the urban settlements where extreme rainfall runoff accumulates along flow paths without being captured by the land drainage/storage systems. Recently, 2D surface flow routing models have been used to simulate the urban surface water runoff originating from point sources (e.g. manholes), using synthetic or model-derived flow hydrographs (e.g. Mignot et al., 2006; Fewtrell et al., 2011). In these studies, the interaction between surface runoff and storm sewer is either considered as insignificant, or represented through a mass loss term determined based on the drainage capacity. Modelling 2D surface water runoff in urban catchment is challenging due to the needs to consider both the hydrological (e.g. precipitation, infiltration and evapotranspiration) and hydraulic processes (surface flow routing), in a topographically complex environment. The representation of spatiotemporal variation in precipitation, and effect of land characteristics (e.g. land use and soil type) is required for the former in order to calculate the right amount of rainfall runoff, while high-accuracy topographic data where topographic connectivity is preserved is essential for routing the surface runoff to the correct places.

More recently, researchers have incorporated direct precipitation into 2D flow routing models in urban environments. Such models can be termed as "hydro-inundation models" whereby hydrological processes are considered simultaneously with floodplain flow routing. Hydrological and inundation processes are two interlinked processes but they have so far been largely investigated in isolation, with hydrological outputs at the catchment-scale used as inputs to surface flow routing at the upstream boundary. Linking these two sub-systems using a unified hydro-inundation model is a logical step towards integrated modelling, especially when multiple entry points exist at the catchment/floodplain boundary. The use of a hydro-inundation model is particularly advantageous for decision makers to evaluate the impact of catchment-wide hydrological processes on urban flood inundation. The role of land management scenarios (e.g. improved storage capacity and improved drainage) can be tested using such models. Whilst commercial software packages already offer such functions, represented by the surface water flood map produced by the EA (2013), research studies coupling hydrological and inundation processes are rare, especially in urban areas. Chen et al. (2009) used a nested approach to incorporate hourly rainfall on a 5 km grid upstream in the upstream catchment and a finer rainfall field of 15-min on a 2 km grid for hydraulic modelling in the downstream. A non-inertial model was used (URM, Chen et al., 2007) and the focus was placed on filtering rainfall events and considering future climate change scenarios derived from UKCP09 predictions. Sampson et al. (2013) presented a modelling study of surface water flooding at a local scale (0.5 km^2) with a uniform rainfall input and a synthetic single point culvert surcharge using a flood inundation model (LISFLOOD-FP), focusing on: (i) routing rainwater from elevated features; and (ii) comparison with commercial modelling packages. Hydrological factors (e.g. infiltration and evapotranspiration) were not considered due to the solely urban nature of their study site, and validation was not undertaken due to limited data availability. In this study, we describe the application of a hydro-inundation model (FloodMap-HydroInundation2D) to investigate the importance of urban and rural land drainage/storage capacity on flood inundation in catchment with a mixture of urban and rural areas, using the June 2007 event in the City of Kingston upon Hull, UK as the baseline simulation.

2. Methods

2.1. The hydro-inundation model used

The model (FloodMap-HydroInundation2D) is developed based on the modified version (local inertial-based) of FloodMap (Yu and Lane, 2006a,b), which is a two-dimensional flood inundation model designed for modelling flood inundation over topographically complex floodplains. The model has been tested and verified with a range of boundary conditions and in a number of environments (Yu, 2005, 2010; Tayefi et al., 2007; Lane et al., 2008; Casas et al., 2010; Yin et al., 2013). It is modified to incorporate the key hydrological processes during an urban storm event into surface flow routing, including infiltration and evapotranspiration.

2.1.1. Surface flow routing

The 2D flood inundation model (FloodMap-Inertial) takes the same structure as the inertial model of Bates et al. (2010), but with a slightly different approach to the calculation of time step. Neglecting the convective acceleration term in the Saint–Venant equation, the momentum equation becomes:

$$\frac{\partial q}{\partial t}+\frac{gh\partial(h+z)}{\partial x}+\frac{gn^2q^2}{R^{4/3}h}=0 \tag{1}$$

where q is the flow per unit width, g is the acceleration due to gravity, R is the hydraulic radius, z is the bed elevation, h is the water depth and n is the Manning's roughness coefficient. Discretizing the equation with respect to time produces:

$$\frac{q_{t+\Delta t}-q_t}{\Delta t}+\frac{gh_t\partial(h+z)}{\partial x}+\frac{gn^2q_t^2}{h_t^{7/3}}=0 \tag{2}$$

To further improve this, one of the q_t in the friction term can be replaced by $q_{t+\Delta t}$ and this gives the explicit expression of the flow at the next time step:

$$q_{t+\Delta t}=\frac{q_t-gh_t\Delta t\left(\frac{\Delta(h_t+z)}{\Delta x}\right)}{(1+gh_t\Delta tn^2q_t/h_t^{10/3})} \tag{3}$$

The flow in the x and y directions is decoupled and take the same form. Flow is evaluated at the cell edges and depth at the centre.

FloodMap evaluates the flow directions in x and y for each pixel at each iteration based on the orthogonal slopes. The flow rate across a cell boundary is calculated using (3) for the two directions associated with the greatest orthogonal slope. Therefore, only positive flow is allowed in each direction. Net inflow is calculated for each pixel based on total inflow and outflow which can then be used to update water depth for the time step. Instead of using a global Courant–Freidrich–Levy Condition (where the time step for the next iteration is calculated based on the maximum water depth and velocity found at the last time step e.g. Yu and Lane, 2006a), the Forward Courant–Freidrich–Levy Condition (FCFL) approach described in Yu and Lane (2011) for the diffusion-based version of FloodMap is used in the inertial model to calculate time step. The maximum time step that will satisfy the CFL condition for a given wet cell is calculated as: