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A step towards considering the spatial heterogeneity of urban key features in urban hydrology flood modelling

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SUMMARY

Some of the major challenges in modelling rainfall–runoff in urbanised areas are the complex interaction between the sewer system and the overland surface, and the spatial heterogeneity of the urban key features. The former requires the sewer network and the system of surface flow paths to be solved simultaneously. The latter is still an unresolved issue because the heterogeneity of runoff formation requires high detailed information and includes a large variety of feature specific rainfall–runoff dynamics. This paper discloses a methodology for considering the variability of building types and the spatial heterogeneity of land surfaces. The former is achieved by developing a specific conceptual rainfall–runoff model and the latter by defining a fully distributed approach for infiltration processes in urban areas with limited storage capacity dependent on OpenStreetMaps (OSM). The model complexity is increased stepwise by adding components to an existing 2D overland flow model. The different steps are defined as modelling levels. The methodology is applied in a German case study. Results highlight that: (a) spatial heterogeneity of urban features has a medium to high impact on the estimated overland flood-depths, (b) the addition of multiple urban features have a higher cumulative effect due to the dynamic effects simulated by the model, (c) connecting the runoff from buildings to the sewer contributes to the non-linear effects observed on the overland flood-depths, and (d) OSM data is useful in identifying pounding areas (for which infiltration plays a decisive role) and permeable natural surface flow paths (which delay the flood propagation).

1. Introduction

Overland flow in urban areas is highly complex because of the interaction with the irregular manmade flow paths. Unless in special cases where the flow remains confined within streets and channels, one-dimensional flow models are not applicable, and two-dimensional (2D) overland flow models must be applied (Vojinovic and Tutulic, 2009; Cea et al., 2010b). Furthermore, vertical drops in flow paths are of paramount importance because two of the crucial assumptions common to all overland flow models fail: namely the assumptions of hydrostatic pressure and small slopes (Cea et al., 2007). Special key features found in urban areas such as buildings and roads, amongst others obstruct the natural flow paths and can cause sudden vertical drops, changes of direction (horizontal view) and localised energy loses to the flow. Thus despite the fact that highly detailed Digital Elevation Models (DEM) exist containing detailed information about the topography of such key features they should not be directly included in the simulation grid of 2D overland flow models, without any further considerations.

The influence of the sewer system in the overland flow is of recognised importance (Djordjevic et al., 2005; Mignot et al., 2014). Earlier attempts to include the simulation of the sewer system were uni-directional (Ellis et al., 1982) meaning that the surcharge water from overloaded manholes was not allowed to return to the sewer system. Cea et al., (2010b) calculated the sewer surcharge in a stand-alone sewer model and used it as input as surface runoff on a 2D Model (Cea et al., 2007). Chen et al., (2005) and Seyoum et al., (2012) overcome the lack of bi-directional interaction by modifying the original code of Storm Water Management Model (SWMM) model when linking with the 2D model. As such the water was allowed not only to surcharge but also to return to the sewer system depending on the hydraulic conditions. This

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type of models are becoming widely used by companies and professionals (Jeskulke et al., 2014; Bernard et al., 2014).

Buildings' geometry causes a change to the overland flow preferential direction as they represent an obstacle to the natural flow paths. In overland flow models buildings have been considered either by increasing the value of roughness in localised areas of interest (Connell et al., 2001; Vojinovic et al., 2011), or with the block elements method, whereby 2D elements are blocked or removed from the simulation grid (Vojinovic, 2010; Russo et al., 2012). A further alternative method consists in increasing the bed elevation of the buildings footprint (Brown et al., 2007; Leandro et al., 2009; Cea et al., 2010a). Common to previous works is the lack of information on the impact of buildings on rainfall–runoff process. Indeed the small percentage of direct runoff (compared to the total rainfall) generated by this feature has led to its disregard. One of the few exceptions is the work by Chang et al. (2015) where the authors utilised the sub-catchments feature from SWMM to model buildings rainfall–runoff processes.

Other key features of particular interest are areas with potential infiltration capacity. For areas where infiltration is likely to occur (e.g. green parks or cemeteries) effective rainfall should replace the total rainfall. Infiltration in overland flow models have been modelled by either reducing it to some initial abstraction value, or considering it as a constant infiltration rate (Russo et al., 2012; Chang et al., 2015) or simply neglecting it (Brown et al., 2007). Indeed at city scale we are often interested in intense short duration rainfall or extreme scenarios (e.g. fully saturated soils), and therefore those simplifications can be deemed acceptable.

This paper aims to develop a methodology for considering the variability of building types and the spatial heterogeneity of different land surfaces in urban flood models at city scale. The key point is to investigate and study how the rainfall–runoff dynamics of urban key features can be conceptualised and included in urban flood models. Particularly this work focus on the inclusion of two urban key features: buildings and permeable land surfaces taken from OSM, including the interaction with the sewer system, surface flow paths and pounding areas. Next section describes the methodology applied with its five distinct modelling levels. Section 3 presents the model verification strategy based on the German design standards DIN. Section 4 presents the results of the buildings conceptual model, and the comparison between all modelling levels. Section 5 discusses the results and the last section concludes the work.

2. Methodology: flood modelling levels

In this study we consider five flood modelling levels (Fig. 1a). By raising the modelling complexity in five levels further details of key urban features can be included into flood simulation results.

2.1. ML1 – 2D overland flood model ($2D_{PDWAVE}$)

The basic model P-DWave is based on the 2D diffusive wave equations discretized in an unstaggered structured grid (Leandro et al., 2014a). It is a first order finite volume explicit discretization scheme that neglects the inertial terms in 2D Shallow Water Equations. The governing equations are written as:

$$\frac{dh}{dt} + \nabla(uh) = R \tag{1}$$

$$g\nabla(h+z) = gS_f \tag{2}$$

where h = water depth [m]; t = time [s]; $u = [u_x \quad u_y]^T$ is the depth-averaged flow velocity vector [–]; u_x = flow velocity in x direction [ms^{-1}]; u_y = flow velocity in y direction [ms^{-1}]; R = source/sink term for rainfall [ms^{-1}]; g = gravity acceleration [ms^{-2}]; z = bed elevation [m]; $S_f = [S_{fx} \quad S_{fy}]^T$ is the bed friction vector [–]; S_{fx} = bed friction slope in x direction [–]; S_{fy} = bed friction slope in y direction [–]. The bed friction is approximated by Manning's formula. The model utilises a prediction–correction wet-dry scheme to obtain absolute mass conservation.

In urbanised areas the existing of sewer network systems may deem the use of 2D flood models unacceptable. Indeed by neglecting the sewer system, the resulting flood volume is unrealistically large. Furthermore, and under certain conditions rainfall events may cause the underground sewer network to surcharge changing significantly the overland flow. In this case the next modelling level should to be applied in which the sewer component is added (Leandro et al., 2011; Borsche and Klar, 2014).

2.2. ML2 – 1D/2D dual-drainage model ($1D_{SWMM}/2D_{PDWAVE}$)

SWMM/P-DWave dual-drainage model links the open-source Storm Water Management Model (SWMM) and the overland flow model described earlier ($2D_{PDWAVE}$). SWMM is a 1D dynamic sewer network model based on the gradually-varied unsteady flow

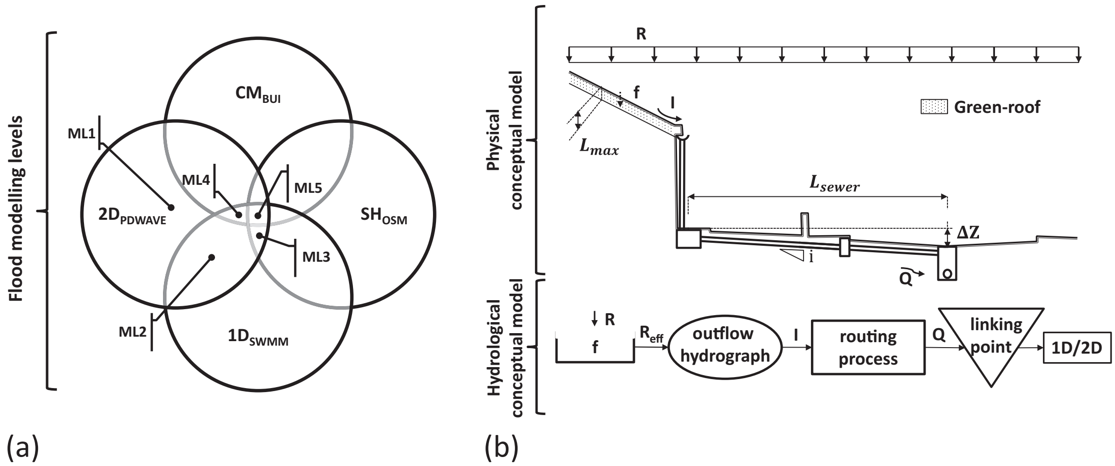

Fig. 1. (a) Overview of the five flood modelling levels and components for urban areas applied in this study. (b) Hydrological conceptual model of a roof connected to the sewer system. The conceptual model input dimensions and setup can be adapted to the building's type of roof and connection (i.e. either to the surface or to the sewer).