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A novel approach to model dynamic flow interactions between storm sewer system and overland surface for different land covers in urban areas

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SUMMARY

In this study, we developed a novel approach to simulate dynamic flow interactions between storm sewers and overland surface for different land covers in urban areas. The proposed approach couples the one-dimensional (1D) sewer flow model (SFM) and the two-dimensional (2D) overland flow model (OFM) with different techniques depending on the land cover type of the study areas. For roads, pavements, plazas, and so forth where rainfall becomes surface runoff before entering the sewer system, the rainfall–runoff process is simulated directly in the 2D OFM, and the runoff is drained to the sewer network via inlets, which is regarded as the input to 1D SFM. For green areas on which rainfall falls into the permeable ground surface and the generated direct runoff traverses terrain, the deduction rate is applied to the rainfall for reflecting the soil infiltration in the 2D OFM. For flat building roofs with drainage facilities allowing rainfall to drain directly from the roof to sewer networks, the rainfall–runoff process is simulated using the hydrological module in the 1D SFM where no rainfall is applied to these areas in the 2D OFM. The 1D SFM is used for hydraulic simulations in the sewer network. Where the flow in the drainage network exceeds its capacity, a surcharge occurs and water may spill onto the ground surface if the pressure head in a manhole exceeds the ground elevation. The overflow discharge from the sewer system is calculated by the 1D SFM and considered a point source in the 2D OFM. The overland flow will return into the sewer network when it reaches an inlet that connects to an un-surcharged manhole. In this case, the inlet is considered as a point sink in the 2D OFM and an inflow to a manhole in the 1D SFM. The proposed approach was compared to other five urban flood modelling techniques with four rainfall events that had previously recorded inundation areas. The merits and drawbacks of each modelling technique were compared and discussed. Based on the simulated results, the proposed approach was found to simulate floodings closer to the survey records than other approaches because the physical rainfall–runoff phenomena in urban environment were better reflected.

1. Introduction

Sewer drainage systems are essential infrastructures in modern cities to convey the runoff during storm events. Like all structural measures, the design capacity of a drainage system limits its ability to cope with runoff that exceeds the design standard. To assess the performance of drainage networks during heavy rainfall events, numerical models have become a popular solution for flood risk analysis. Among numerical models, one-dimensional (1D) sewer flow models (SFMs) are the most commonly used tool because of the relatively simple model construction, the high efficiency and the shorter runtime for simulations. Many 1D software packages

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Abbreviations: 1D, one-dimensional; 2D, two-dimensional; ACC, accuracy; DEM, digital elevation model; FN, false negative; FP, false positive; GIS, geographic information system; OFM, overland flow model; PPV, positive predictive value, precision; SFM, sewer flow model; SWMM, Storm Water Management Model; TN, true negative; TP, true positive; TPR, true positive rate, sensitivity.

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are currently available to simulate the hydraulic performance of urban drainage systems. The Storm Water Management Model (SWMM) is an open-source model with complete functions (Rossman, 2010) such that it has been widely adopted in academic studies (Oraei Zare et al., 2012; Ranger et al., 2011) and by commercial software packages like MIKE SWMM (DHI Software, 2014) and XP-SWMM (XP Solutions, 2013). Other software packages with different hydraulic solvers, such as MIKE MOUSE (DHI Software, 2014) and InfoWorks ICM (Innovyze, 2014) are also popular in industrial practices.

The sole use of a 1D SFM can only predict, in terms of ground surface, the surcharge volume from the drainage system, which is translated into the flood depth of a sub-catchment using a depth-volume or area-volume function. This approach assumes no flow interaction between sub-catchments, which oversimplifies the surface runoff[1] dynamic, especially for flat areas, such that Djordjević et al. (1999) proposed the 1D/1D dual drainage approach, which regards surface flow paths and detention ponds as a further drainage network to convey surface runoffs and to improve the modelling result. With an improved data acquisition algorithm to enhance the representation of surface drainage network, the 1D/1D dual drainage models can produce accurate results along pathways and inside ponds (Allitt et al., 2009; Leandro et al., 2009; Maksimović et al., 2009). Nevertheless, the assumption that the flow is confined by the drainage system becomes invalid when the flood depth is greater than the bank of a flow path or the crest of a pond, the runoff movement no longer follows the predetermined pathways and the overland flooding outside pathways and ponds occurs. The 1D SFMs and the 1D/1D dual drainage models will not be able to simulate the situation properly and the two-dimensional (2D) overland flow model (OFM) is required for such analysis (Chang et al., 2011; Kao and Chang, 2012).

The growing capability of computing tools, the availability of high-resolution data and the demand for detailed information on the location of floods and their magnitude, have increased the applications of 2D OFMs in recent years (Néelz and Pender, 2013). To simulate detailed flood propagation on the ground surface, many physical-based 2D OFMs for solving shallow water equations (SWEs) have been developed. Hunter et al. (2008) and Néelz and Pender (2013) have compared the performance of a wide range of 2D flood models using common test cases. These include academic research models (e.g. LISFLOOD-FP, Bates et al., 2010; UIM, Chen et al., 2012) and commercial software (e.g. MIKE FLOOD, DHI Software, 2012; ISIS 2D, Halcrow, 2012; InfoWorks ICM, Innovyze, 2012). The models adopt different governing equations (such as full SWEs or simplified approximation), computing grids (irregular meshes or regular cells) and parallelisation techniques (OpenMP, OpenMPI and GPU) to simulate flooding. The results (Néelz and Pender, 2013) showed that although most 2D flood models can produce similar results, the details for some critical conditions would vary significantly due to the assumptions or nature of different models.

The Environment Agency developed the first national surface water map for England and Wales using the JFlow-DW (Lamb et al., 2009) on a five metre resolution grid that disregarded the function of the sewer network. This type of approach is referred to as the 2D OFM only in the later sections in the study. Subsequently, the updated Flood Map for Surface Water (uFMfSW) for England and Wales (Environment Agency, 2013) on a 2m resolution grid was produced using an improved model JFlow+ 2D (Crossley et al., 2010a, 2010b). The function of the sewer network was represented by subtracting a constant rate of rainfall in the uFMfSW. It is herein referred to as the 2D OFM with rainfall reduction approach. Chen et al. (2009) represented the function of sewer drainage system with a constant infiltration rate in the 2D OFM in a case study in south east London. Unlike the reduced rainfall rate used in the uFMfSW (Environment Agency, 2013) such that the excess runoff cannot be collected by sewer system in the 2D OFM, Chen et al.'s approach (2009) allows the surface water to be drained when the capacity in the sewer network is available.

Hsu et al. (2000) used the surcharge hydrographs at manholes calculated by the SWMM as inputs to a 2D OFM to simulate urban flooding. The assumption that the flow can only move from the sewer system to the ground surface, but not vice versa, failed to accurately describe the phenomenon that occurs where surface runoff re-enters the drainage system. Hence, in such a combined SFM/OFM approach, the flood extent and depths tend to be overestimated in downstream areas. The initial rainfall–runoff process was simulated by the RUNOFF module of SWMM and applied to manholes directly as the input of the EXTRAN module. Therefore, the information of flooding during this initial phase within manhole sub-catchments was presented as excess volume, as with the surcharge volume in the 1D SFM only approach. The detailed flood dynamic on the ground surface in this phase was disregarded.

To improve the overestimation drawback of the combined SFM/OFM approach, some academic researchers have attempted new coupling methodologies (Hsu et al., 2002; Seyoum et al., 2012). The 1D SFM and the 2D OFM use different computing time steps due to the nature of the problem (Chen et al., 2007), and the 2D OFMs often adopt adaptive time steps to speed up simulations (Bates et al., 2010; Hunter et al., 2005). To avoid further errors occurring in model coupling because of different time steps being used in different models, Chen et al. (2007) suggested a solution for time synchronisation between 1D SFM and 2D OFM to ensure exact values are exchanged during model communications.

Commercial software developers also provide various 2D modelling products that are bi-directionally coupled with 1D channel or 1D sewer models. SOBEK is a fully coupled hydraulic model that is able to simulate sewer, channel and overland flows concurrently (Deltares systems, 2014). In SOBEK, three manhole types, such as closed, reservoir and loss, can be set for modelling. The closed type does not allow the water to escape from the 1D sewer system such that no flow exchange with the 2D overland surface will occur. For the reservoir type, a storage area above a manhole is defined as a pond for keeping the surcharged water to represent the flooding on the 2D overland surface, despite no 2D OFM being involved. For the loss type, the water exceeding the surface level above a manhole will be removed from 1D SFM and added to the 2D OFM. XP-SWMM 2D (Phillips et al., 2005) was developed by adding the TUFLOW 2D module (Syme, 2001) with the XP-SWMM 1D model to enhance its capability for urban flood modelling. Similar integration was also applied to couple the 1D river, the 2D overland and the 1D sewer models as the ISIS-TUFLOW-PIPE (Halcrow, 2013). The MIKE Urban (DHI Software, 2014) has seen the integration of MIKE 11, MIKE MOUSE/SWMM and MIKE FLOOD models to simulate combined river, sewer and floodplain modelling. Coupling the 2D cells within a given radius from a manhole with sewer nodes is used (DHI Software, 2014) for collecting the runoff from or distributing the surcharge to the 2D computing domain. Similarly, the InfoWorks 2D module also has been integrated with the InfoWorks CS and InfoWorks RS for 1D/2D modelling in both sewers and rivers. InfoWorks links the 2D mesh to sewer nodes as 2D, Gully 2D or Inlet 2D types and uses equations corresponding to those types for determining the interacting discharge between the 1D sewer and 2D overland flow (Innovyze, 2014).

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[1] In this paper, the 'surface runoff' represents the water flow on the surface that can be simulated by either 1D OFMs or 2D OFMs.The 'overland flow' means the water travelling outside the pre-defined surface pathways (e.g. roads, open drainage channels), which can only be described by 2D OFMs.