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Ensemble urban flood simulation in comparison with laboratory-scale experiments: Impact of interaction models for manhole, sewer pipe, and surface flow

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ABSTRACT

An urban flood is an integrated phenomenon that is affected by various uncertainty sources such as input forcing, model parameters, complex geometry, and exchanges of flow among different domains in surfaces and subsurfaces. Despite considerable advances in urban flood modeling techniques, limited knowledge is currently available with regard to the impact of dynamic interaction among different flow domains on urban floods. In this paper, an ensemble method for urban flood modeling is presented to consider the parameter uncertainty of interaction models among a manhole, a sewer pipe, and surface flow. Laboratory-scale experiments on urban flood and inundation are performed under various flow conditions to investigate the parameter uncertainty of interaction models. The results show that ensemble simulation using interaction models based on weir and orifice formulas reproduces experimental data with high accuracy and detects the identifiability of model parameters. Among interaction-related parameters, the parameters of the sewer–manhole interaction show lower uncertainty than those of the sewer–surface interaction. Experimental data obtained under unsteady-state conditions are more informative than those obtained under steady-state conditions to assess the parameter uncertainty of interaction models. Although the optimal parameters vary according to the flow conditions, the difference is marginal. Simulation results also confirm the capability of the interaction models and the potential of the ensemble-based approaches to facilitate urban flood simulation.

1. Introduction

Flood disasters are the main cause of losses arising from natural hazards and are responsible for a great number of damaging events that threaten human safety (Noh et al., 2013). With increasing urbanization and climate change, many cities face rising flooding risks, which affect people's lives and the economy. However, an urban flood is a phenomenon that is affected by various uncertainty sources such as input forcing, model parameters, complex topography, and dynamic interaction among different flow domains in surfaces and subsurfaces. Therefore, integrated approaches are required to find proper solutions on urban floods.

There have been considerable advances in urban flood modeling. Numerous numerical models such as the Storm Water Management Model (SWMM, (US EPA. Storm Water Management Model (SWMM) 2015)), Illinois Urban Drainage Area Simulator (ILLUDAS, (Terstriep, 1974)), LISFLOOD-FP (Neal et al., 2011), and MOUSE (Mark et al., 1998) have been developed and applied to various urban and peri-urban areas in order to simulate flows in the sewer network and flows caused by inundation from rivers. In recent years, advanced numerical schemes have been presented to precisely simulate flow in complex urban topography (Chen et al., 2012a,b, 2015 Schubert and Sanders, 2012, Smith et al., 2015, Leandro et al., 2014a, 2016), to include building treatment (Chen et al., 2012b, Schubert and Sanders, 2012, Leandro et al., 2016), to parallelize 2D overland flow models (Smith et al., 2015) or dual-drainage models (Leandro et al., 2014a), and to simulate manhole cover displacements during surcharge events (Chen et al., 2015). The adaptation of geographic information system (GIS) data has contributed to fundamentally increasing the credibility and applicability of inundation modeling in urban surface areas

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(Smith, 1993, Zhang and Pan, 2014, Zhang et al., 2014, Gallegos et al., 2009, Leitão et al., 2009). As Niemczynowicz, (1999) stated, rainfall input has been considered as one of the drawbacks in the discipline of urban floods. However, advances in the measurement and prediction of urban rainfall using technologies such as radar and microwave networks have increased our capability to gather sufficient information on the temporal and spatial variations in rainfall processes in relatively small urban catchments (Fletcher et al., 2013, Schellart et al., 2012, Bates and De Roo, 2000, Khu et al., 2006). In addition, the impact of climate change on urban floods has been analyzed in various studies (Semadeni-Davies et al., 2008, Huong and Pathirana, 2013).

High imperviousness and short time of concentration are basic features of urban hydrology. Under such conditions, sewer drainage networks play an essential role in modern cities to transport runoff during storm events (Chang et al., 2015). To simulate the interactive exchange of storm water in the sewer system and on the surface, the dual drainage concept has been introduced and utilized for various models (Chang et al., 2015, Djordjević et al., 1999, Lee et al., 2015, Leandro et al., 2009, Fraga et al., 2015), and recently validated with experimental work (Fraga et al., 2015). The numerical coupling of surface and sewer flow at the interface of the two zones is an essential feature of the dual drainage concept, which facilitates the simulation of urban floods induced by surcharge from sewer pipes.

Meanwhile, experimental studies have been conducted to understand complex flow dynamics in man-made facilities and natural channels and to identify proper values of model parameters such as weir and orifice coefficients; such studies has attracted the attention of researchers since the early year of hydraulic engineering (Chow, 1959, Clemmens et al., 1984, Guven et al., 2013). In the last decades, there have been improvements through experimental research on different aspects of urban flooding such as surcharge or transient flow in a sewer (Lopes et al., 2015, Vasconcelos et al., 2006, Li and McCorquodale, 1999, Bazin et al., 2014) and flow exchange between the surface and sewer pipe (Martins et al., 2014). However, as Freni et al., (2009) and Kim et al., (2014) have mentioned, there remains difficulties in model calibration due to sensitivity of model parameters in drainage pipes. Although the flood marks or maximum inundation area are widely used as an evaluation metric for inundation simulation, such information is not necessarily sufficient to quantitatively analyze and parameterize interaction models. As such, limited knowledge is currently available on how flow interaction among different domains affects urban floods.

Given the limitations of both simulation models and experiments in analyzing urban floods, probabilistic approaches that consider inherent uncertainty sources may have certain advantages in improving the prediction and understanding of urban floods. Sun et al., (2012) defined two different types of uncertainty, i.e. aleatory and epistemic uncertainty, in urban flood simulation. An aleatory uncertainty source, which represents randomness in samples, includes uncertainty in hyetographs and rainfall depth or duration in return period analysis. On the other hand, epistemic uncertainty includes the parametric uncertainty of an urban flood model; epistemic uncertainty results from a lack of knowledge of fundamental phenomena and is related to our ability to understand, measure, and describe the system under study. According to another common classification of uncertainty (Beven, 2008, Gupta et al., 2012), urban flood modeling contains uncertainty from three sources: the model structure, parameters, and observation. Additional discussion on probabilistic approaches and applications in environmental modeling can be found in literature (Beven and Freer, 2001, Blasone et al., 2008, Deletic et al., 2012). Based on the above two classifications, the uncertainty of interaction models in urban flood simulation is considered as an epistemic uncertainty source related to the uncertainty of parameters as well as the model structure. Discussion on the uncertainties in urban flood modeling and stochastic applications can also be found in a few recent studies (Djordjević et al., 2014, Leitão et al., 2015).

In this paper, an ensemble method for urban flood modeling is presented to consider the parameter uncertainty of interaction models among a manhole, a sewer pipe, and surface flow. Laboratory-scale experiments on urban flood and inundation are performed under various steady and unsteady-state flow conditions to investigate parameter uncertainty. Through comparison with experimental results, optimal parameters are selected for each simulation case and the identifiability of parameters is analyzed. It is worthy to note that in this study our main interest is to assess the proper ranges and uncertainty of model parameters using conceptual models for the dynamic interaction of urban floods; exploring the structural uncertainty of the models is beyond the scope of this study. The experimental setup is described in Section 2. The numerical model of an urban flood, including a 2D surface flow model, storm drain model, and 1D sewer pipe flow model, is presented in Section 3. The interaction model that combines three component models is also presented in Section 3. In Section 4, the model performance and parameter uncertainty are discussed. Conclusions are drawn in Section 5.

2. Laboratory experiment

2.1. Experimental setup

Fig. 1 shows the side and plan views of the laboratory experimental facility, which is located at the Ujigawa Open Laboratory of the Disaster Prevention Research Institute (DPRI), Kyoto University, Japan, and consists of three parts: the rainfall simulator, ground surface, and sewer pipe system. The scale of this experimental facility is assumed to be 1/20th of the real-world scale using the Froude similarity law. Twenty nozzles spray water onto the ground. The ground space around the nozzles is surrounded by a transparent curtain to force the artificial rainfall (i.e., sprayed water) to fall onto the ground surface in the experimental domain. The maximum experimental rainfall of 30 mm/h in prototype scale is similar to the maximum rainfall of 130 mm/h in the real-world scale approximately. This rainfall simulator is, however, not used because the amount of rainfall is too small to effect the inundation on the ground (Lee et al., 2013).

The ground surface has a flat inundation basin (10 m long and 2 m wide), on which is located a 0.5 m wide road and a 0.15 m wide sidewalk. Ten buildings are present on each side of the basin, and 20 storm drains (0.05×0.05 m) are present on the road. The storm drain is the cover of a drain box ($0.05 \times 0.05 \times 0.05$ m). Ten drain boxes exist on each side of the road and are connected to each other by a drain channel with a 0.015×0.025 m cross section. Note that the drain channel was initially made to represent realistic conditions in the sewer but was not used in either experiments or simulations because the channel was saturated initially and the friction from this structure was negligible because the type of material used (acryl plastic). One circular pipe that is 0.05 m in diameter, 11.6 m long, and has a slope of 1/971 is placed below the ground surface. This pipe can be divided into 10 segments, each of which has two tubes that connect to the drain box and the top of a building (Fig. 1 (a)) and a piezometric tube to measure a change in the piezometric head in the pipe. Variations in the inundation depth on the ground surface are measured at H1 and H2, as shown in Fig. 1 (b). A cross section of the experimental setup is shown in Fig. 2. The light blue line indicates the connection tubes between building roofs and the sewer pipe, whereas the dark blue line indicates the connection between a drain box and the sewer pipe. Exchange discharge between connected parts due to a difference in the piezometric head is transported through these tubes. For