A computationally efficient urban flood model with a novel approach for determining water discharge through complex drainage network

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Highlights

- A computationally efficient urban flood model was developed.
- A novel approach for determining integrated surface water discharge was proposed.
- Real-time forecast is expected to be conducted by using this model in the near future.

Introduction

It is widely recognized that urban cities around the world will face more severe challenges against flooding due to continuing loss of permeable surface area and increasing frequency of heavy rainfall (Arnbjerg-Nielsen et al. 2012). Real-time forecast and warning of urban flooding have become more and more important for disaster mitigation while this need has not yet been fulfilled. Compared to real-time forecast approaches based on empirical or pre-simulated scenarios, the physics-based model is more powerful in its applicability and predictive skills of flooding under various conditions (Sanuki et al. 2017). One general method for decreasing the computational cost of the physics-based model to achieve real-time application is using coarse grid for the surface flow model, however, the coarser grid system may end up to decrease the accuracy especially for the flow from the land surface to the sewer system. While most of the previous studies mainly focus on such trade-off relationship between predictive accuracy and computational efficiency of two-dimensional (2D) flow on the ground surface, the effect of coarse grid on computation of the underground sewer system is not studied well. This study proposed an integrated urban flood model with a novel approach for determining water discharge through complex drainage network, which not only enhances computational efficiency but also improves the predictive accuracy of the flow from the land surface to the sewer system.

Methodology

Urban flood model

The urban flood model consists of a one-dimensional (1D) river flow model, a 1D sewer network model and a 2D surface flow model. The model can seamlessly compute the flow dynamics in the river, in the sewer network and over the land surface. **Figure 1** illustrates the simulation processes and the interaction between each sub-model. **Figure 2** shows the study area with digital elevation data.

Water discharge from ground surface to sewer network

Generally, most of the effective rainfall is transported to the sewers from the building roof and through surface water discharge facilities such as street gutters and catch pits. Discharged water is collected and finally enters the underground sewer network. It is considered that the capacity of surface water discharge facilities is proportional to the level of completeness of the drainage network in each sub-

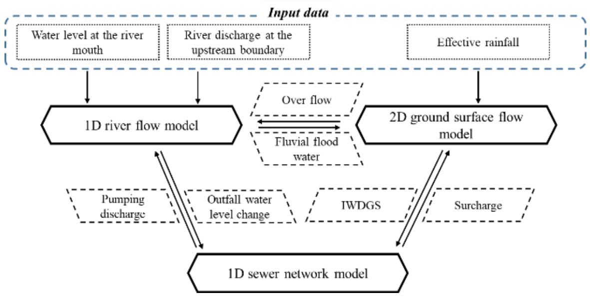

Figure 1. Model description

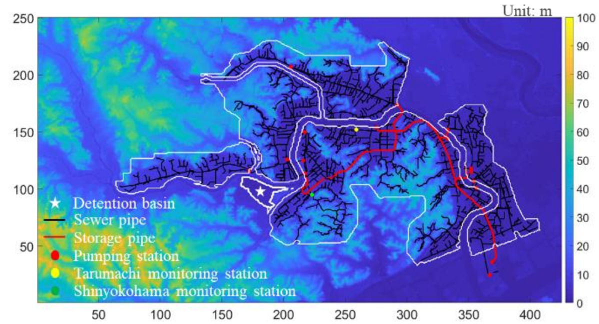

Figure 2. Digital elevation map of the study area. Horizontal and vertical axis is the grid index of the 2D surface flow model

catchment. Thus, the discharge capability of each grid in the 2D surface flow model can be determined by the ratio of roof area and the level of completeness of the drainage network. We therefore propose the following equation to represent q_{out}, discharge rate of surface water per unit surface area at each grid to each manhole nearby,

$$q_{out} = \frac{\alpha}{N} R_{bc} \frac{L}{S} \sqrt{gH} \Delta x \Delta y \qquad \text{Eq. 1}$$

where α is a calibration factor with a dimension of length, N is the number of nearest manholes from the grid with a size of $\Delta x \Delta y$, R_{bc} is the building coverage ratio of each grid, which is assumed to be equal to the roof area ratio in each grid regardless of the roof shape for simplicity, S is the sub-catchment area, L is total length of sewers in the sub-catchment area, and H is the water depth on a target grid. Here we assume that discharge rate is proportional to L/S.

Application

The Tsurumi river basin was selected as the study area of model application (**Fig. 2**). It is located in the city of Yokohama, one of the largest coastal cities in the world. The modelling region covers an area of approximately 49 km^2. There are 50,971 sewer pipes with inner diameter larger than 200 mm connected by 51090 manholes in the modelling area. The grid size of the 2D surface flow model was set to be 40 m and only sewer pipes with inner diameter larger than 600 mm were considered in the 1D sewer network model thus the computational cost decreases significantly since the total number of pipes and manholes reduces from more than 100 thousand to 17,606. We adopted eight rainfall events occurred in 2019 with different characteristics to validate the developed urban flood model. Measurement of water depth in the sewer network was used for evaluating the accuracy of the model.

Results and discussion

Figure 3 shows the time series of measured and simulated water level of the 8 rainfall events at Tarumachi monitoring station. The simulation accuracy was greatly improved by employing the proposed discharge approach for all the rainfall events. The time of the abrupt water level rise was well reproduced by the model when employing the surface water discharge approach. Without the proposed discharge model, on the contrary, the time of abrupt water level rise was delayed for more than several hours compared to the measured data. The simulation time for one rainfall event (24 h simulation, 0.5 s time step) was around 8 min by use of a typical desktop computer, which indicated that fast prediction of urban flood was achieved with the developed approach. Through a sensitivity analysis, it is found that several parameters such as, the accuracy of rainfall intensity, the discharge coefficient α in Eq.1 and the friction factor of the sewers can largely affect the predication accuracy. As the precipitation forecast is now available in many cities in the world, real-time forecast of urban flood is possible by using this model if we use a rainfall-runoff model to predict the upstream river discharge.

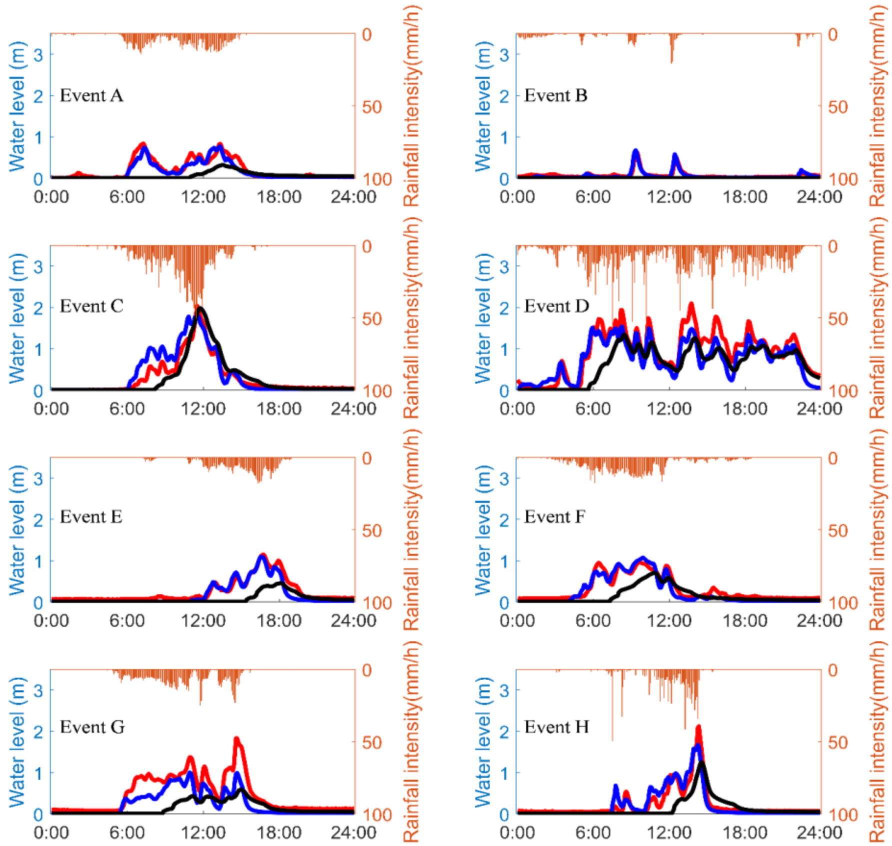

Figure 3. Time series of measured and simulated water level of 8 rainfall events. Red line: measurement; blue line: simulation with surface water discharge approach; black line: simulation without surface water discharge approach.

Conclusions and future work

In this paper, an efficient urban flood model was developed which is consisted of a 1D river flow model, a 2D surface flow model and a 1D sewer network model. The discharge capacity loss of the surface water due to the simplification of the drainage network and the use of coarse grid was compensated by a novel surface water discharge approach which assumed that the surface water was mainly transported by the buildings and water discharge facilities. The developed model was applied to the Tsurumi river basin which is a typical densely populated lowland. Simulated water level agreed well with the measurement with the surface by use of the proposed discharge approach. Computational cost is relatively low and real-time predication is possible by use of this model. Sensitivity analysis showed that the model result was largely affected by various parameters. Therefore, it is of great importance to modify the model setup by using the various data such as the water level measurement, operation records of the pumping stations when conducting real-time prediction. Further studies are necessary to determine the upper limit of the parameter α which may be possible if inundation is triggered by heavy rainfall events. In addition, the equation to describe the discharge capacity is expected to be improved for better representing the local features of drainage facilities.

References

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