An Integrated Modeling Approach to Predict Flooding on Urban Basin

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Abstract

Correct prediction of flood extents in urban catchments has become a challenging issue. The traditional urban drainage models that consider only the sewerage-network are able to simulate the drainage system correctly until there is no overflow from the network inlet or manhole. When such overflows exist due to insufficient drainage capacity of downstream pipes or channels, it becomes difficult to reproduce the actual flood extents using these traditional one-phase simulation techniques. On the other hand, the traditional 2D models that simulate the surface flooding resulting from rainfall and/or levee break do not consider the sewerage-network. As a result, the correct flooding situation is rarely addressed from those available traditional 1D and 2D models. This paper presents an integrated model that simultaneously simulates the sewerage-network, river-network and 2D mesh-network to get correct flood extents. The model has been successfully applied into the Tenpaku basin (Nagoya, Japan), which experienced severe flooding with a maximum flood depth more than 1.5 m on September 11, 2000 when heavy rainfall, 580 mm in 28 hrs (return period > 100 yr), occurred over the catchments. Close agreements between the simulated flood depths and observed data ensure that the present integrated modeling approach is able to reproduce the urban flooding situation accurately, which rarely can be obtained through the traditional 1D and 2D modeling approaches.

Keywords

Urban drainage; Integrated model; Flood simulation; Storm water management

INTRODUCTION

Flooding on urban basins is intensifying due to rapid urbanization. Flooding primarily occurs because of drainage congestion of inland flow and/or over bank flow of river during severe rainfall event. Rapid urbanization is causing a major change in rainfall-runoff phenomenon and the drainage system as well. The overland flow pattern is becoming complex due to huge structural development, and therefore, the correct prediction of surface runoff is becoming a challenging issue.

Traditional one-phase sewerage-network model may be able to simulate the drainage system correctly until there is no overflow from the network inlet or manhole. When such overflows exist due to insufficient drainage capacity, then it is difficult to reproduce the actual flooding condition using this traditional one-phase simulation technique. In one-phase simulation one can store the excess water that overflows from a manhole by considering a virtual storage basin above the manhole.

Sewerage-network can get the stored water back through the same manhole when the system capacity regains. However, how to determine the dimension of virtual basin is another problem. In reality, when the manhole is located on a relatively higher elevation, then the overflowed water moves further downstream and possibly enters into the sewerage-system again through another inlet. This situation is often observed in urban drainage basins. Unfortunately, the traditional one-phase modeling approach is unable to handle this situation. Alternatively, by giving some extra efforts the two-phase modeling technique can be employed where the street-network is simulated as open channel to drain the water overflowed from the sewerage-network, and a better representation of flooding scenario can be obtained, if the flood extents do not expand beyond the streets. On the other hand, the traditional 2D mesh model usually does not consider the sewerage-network in simulation of surface flooding resulting from rainfall and/or levee break, and usually produces higher flood extents than the reality. Therefore, the correct flooding situation can rarely be addressed using those available traditional models as the integration of all drainage elements is not considered. The integrated flood simulation model, which is capable to incorporate all the drainage elements and their interactions properly, is necessary for an accurate prediction of urban flooding.

This paper presents the development and application of an integrated model in which the sewerage-network, river-network, mesh-network, etc. almost all the drainage elements have been considered in order to get a correct prediction of flood situation.

MODULES AND THEORY

The present integrated model is constructed basically by joining the EXTRAN module of Storm Water Management Model of United States Environmental Protection Agency (EPA-SWMM) and a traditional flood simulation model (FLDSIM) developed by National Institute for Land and Infrastructure Management (NILIM), Japan. EXTRAN module is responsible for the 1D simulation of sewerage-network. FLDSIM module has two different parts: (i) MESHSIM to simulate the 2D overland flow using mesh-network and (ii) RIVSIM to simulate the 1D flow through river-network. MESHSIM and EXTRAN are interconnected through the sewerage inlet or manhole and the flow interaction is limited by a control structure (weir or orifice). RIVSIM and MESHSIM are interconnected through the condition setting for the levee break or bank overtopping and the flow interaction is controlled by series of weir equations developed in NILIM.

The flows in sewerage- and river-network are simulated using 1D unsteady flow equations, whereas 2D depth-averaged unsteady free surface flow equations are used in simulating flows in mesh-network. The surface runoff resulting from rainfall or/and over bank flow of river is simulated through mesh-network. The meshes are connected to sewerage inlets/manholes, which allow the surface runoff to enter into the sewerage-network before causing ground flooding. Further, if any location of the sewerage-network is unable to drain any additional inflow coming from upstream pipes, then the overflow from sewerage- to mesh-network occurs. This overflowed water then moves further downstream through mesh-network and enters into another sewerage inlet where there is sufficient capacity. The flow interactions between mesh- and sewerage-network are controlled by a virtual weir (or orifice) setting along the rim of manhole. This virtual weir (or orifice) substitutes the inlet grating and the crest level of the weir is same as ground elevation of the connected mesh. Flow interactions between river- and mesh-network are also controlled by a weir, which is dynamically set at the level of broken levee. The dimension and crest level of weir change with time according to the condition of broken levee. Pump, weir, orifice, diversion, gates, culverts, etc. all kinds of hydraulic (control) structures either in MESHSIM or EXTRAN use their own specific governing equations to simulate the flow through them.

RUNOFF module of EPA-SWMM, which simulates the surface runoff resulting from rainfall and creates the inflow hydrographs for EXTRAN module, is replaced by MESHSIM in present model, and therefore, all rainfall eventually comes into MESHSIM. Fig.1 shows the interaction among different modules. The flow interaction between EXTRAN and MESHSIM occurs at each time step. The detail description of EXTRAN module can be found in Huber and Dickinson (1988) and Roesner et al. (1988), whereas the FLDSIM is described in Dey (2004). However, a brief outline of the modules, as described in original references, is discussed in following paragraphs.

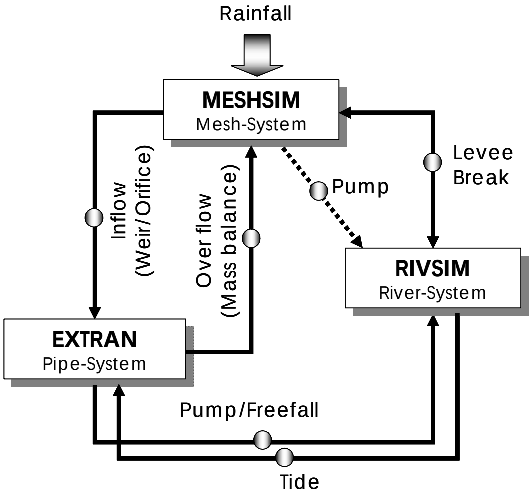


Fig.1 Interaction among different modules

EXTRAN Module

EXTRAN is a hydraulic flow routine model for open channel and/or closed conduit systems. EXTRAN module receives inflow at specific manhole locations generated from MESHSIM module. The module performs dynamic routine of storm water flows through the sewerage-network to the outfalls to the receiving water system. This module can handle branched or looped networks flow, backwater effect, free-surface and pressurized flow. The basic differential equations to govern the gradually varied unsteady flow are as shown below.

Continuity: $\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0$ (1) ; Momentum: $\frac{\partial Q}{\partial t}+\frac{\partial (Q^2/A)}{\partial x}+gA\frac{\partial H}{\partial x}+gAS_f=0$ (2)

where, x= x-direction; t= time; g= acceleration due to gravity; H= water level; S_f= friction slope defined by Manning's formula; Q= flow through link; A= link cross-section area.

MESHSIM Module

MESHSIM is a 2D hydraulic flow routine model for the rectangular mesh systems. MESHSIM module receives rainfall and/or lateral inflows from external sources. The module performs dynamic routine of storm water flows through the mesh-network to the outfalls to receiving water system. The basic differential equations to govern the gradually varied unsteady flow are as shown below.

Continuity: $$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \qquad (3)$$

Momentum: $$\frac{\partial M}{\partial t}+\frac{\partial uM}{\partial x}+\frac{\partial vM}{\partial y}+gh\frac{\partial H}{\partial x}+\frac{1}{\rho}\tau_x=0 \qquad (4)$$

$$\frac{\partial N}{\partial t}+\frac{\partial uN}{\partial x}+\frac{\partial vN}{\partial y}+gh\frac{\partial H}{\partial y}+\frac{1}{\rho}\tau_y=0 \qquad (5)$$

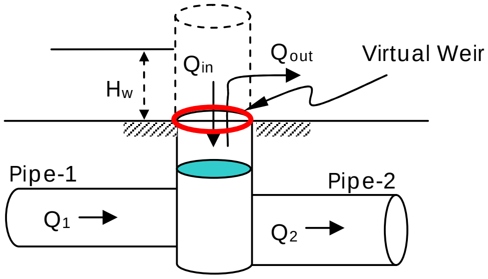
where, H= water elevation; h= water depth; u and v= velocities in x- and y-direction; g= acceleration due to gravity; ρ= density of water; M and N= flow fluxes in x- and y-direction (M=uh, N=vh); τ_x and τ_y= shearing stresses in x- and y-direction. The shearing stress terms are expressed using Manning's roughness coefficient (n), which are $\tau_x=\frac{\rho g n^2 \bar{u}\sqrt{u^2+v^2}}{h^{1/3}}$ and $\tau_y=\frac{\rho g n^2 \bar{v}\sqrt{u^2+v^2}}{h^{1/3}}$.

RIVSIM Module

RIVSIM is a 1D hydraulic flow routine model for river-system. RIVSIM module receives inflow at specific locations generated by MESHSIM and/or EXTRAN module. The module performs dynamic flow routine through river-network. This module can handle branched or looped networks flow, backwater effect and levee-break effect. The basic differential governing equations for the gradually varied unsteady flow are basically the same as EXTRAN.

INTERFACE Module

INTERFACE module is the virtual structure (weir or orifice) between mesh and manhole that controls the inflow to EXTRAN from MESHSIM. The virtual weir has been used as interface module in this simulation. Ground elevation is considered as weir crest and mesh depth is considered as driving head of weir. Weir length is the user input value and can be determined from the consideration of spacing and shape of inlet gratings. Overflow occurs if the manhole water level exceeds the ground elevation to satisfy the continuity at manhole ($\sum Q \equiv 0$). The overflow is calculated as $Q_{out} = \sum Q$. Fig.2 shows the schematic diagram of the INTERFACE module.



$$Q_{in}=C_w L_w H_w^{3/2}$$

where,
Q_{in} =Inflow to EXTRAN
C_w =Flow coefficient= 1.7
H_w=Mesh water depth
L_w=Length of virtual weir

Fig.2 Interface module to control flow interaction between MESHSIM and EXTRAN

APPLICATION OF MODEL

Description of Site

The study area, where the present integrated modeling approach has been applied, is the Tenpaku-river basin of Nagoya city, Japan located in the province of Aichi, about 400 km west of the capital city Tokyo (Fig.3). The drainage area covers approximately 270 ha and is served by a complicated looped drainage network with two pumping stations located at most downstream that drive the flows into Tenpaku-river. The area is separated by a high (>3 m) embankment from the main receiving body, Tenpaku river. Gravity drain of storm runoff into the receiving body is not possible; all loads must be pumped out into the receiving body. The basin experienced severe flooding with a maximum flood depth more than 1.5 m on September 11, 2000 when heavy rainfall (return period > 100 yr) occurred over the catchment. Resident experienced knee-deep water on the streets. Daily activities in parts of the city were nearly paralyzed and heavy traffic jams occurred due to stored water on the streets.

Fig.3 Location of the site

Model Setup

Detailed integrated hydrodynamic model for the existing topographic and drainage configuration of the basin has been created based on the relevant structural, topographical, hydrological and demographic information. The data was either available in a directly usable format, or it has been digitized from the maps and subsequently processed into appropriate format. Surface network was created using 50 X 50 m mesh as more precise topographic data was not available for this site at that time. The sewerage-network of the study area is quite complicated. The looped- and branched-network includes a wide range of closed pipes and open channels. There are so many detailed elements (pipe & nodes) at most upstream of the sewerage-network. The pipes less than 40 cm diameter are ignored to make the model less complicated and to avoid the numerical instability. The entire modeling domain has been divided into three sub systems (Fig.4):

- i) Subsurface-system that includes all the pipe, open-channel or river-network.
- ii) Surface-system that includes 2D surface cells (mesh) through which the runoff (overland flow) from rainfall or any other sources is simulated.
- iii) The interface module that makes a connection between surface- and subsurface-system.

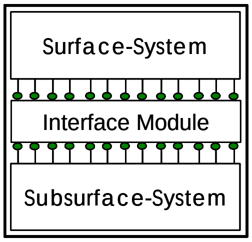


Fig.4 Sub-systems in model

To ensure the accurate flood prediction and to get simultaneous interaction between subsurface- and surface-system it has been decided that the overland flow should be simulated through 2D mesh-system and the RUNOFF module of EPA-SWMM would not be used. Open channels and pipes have been simulated through 1D link-node concept. As mentioned earlier, the inflow from surface- to subsurface-system has been controlled by a system of virtual weirs set along the rim of manhole at the ground level. The overflow from subsurface- to surface-system happens when the node water level exceeds ground elevation and the downstream pipe or open channel capacity is not enough to drain all upstream flows. Fig.5 shows the flowchart on how the integrated model works.

In addition to the integrated approach where sewerage- and mesh-network have been simulated simultaneously at every time step (Case A), an additional simulation of exactly same model excluding sewerage-network (Case B) also has been done to realize the differences in simulated flood extents in two different approaches. The DTM (digital terrain model) layer and the sewerage-network are shown in Fig.6. The overview of the model elements in Case A and Case B is presented in Table 1.

Simulation

Application of the present integrated simulation technique to reproduce the flood situation of Tenpaku-river drainage basin was under the load of a heavy rainfall, which occurred over the basin on September 11, 2000 (Fig.7). Two pump stations located most downstream pumped the drained water into Tenpaku-river (Fig.6). The model has been properly calibrated for the surface roughness and for the length of the virtual weirs used in the interface module. Manning's roughness 0.04 and weir length 3.14 m have been used in entire simulation domain.

Result and Discussion

The overall water balance of simulation was quite satisfactory (< 1%). The total rainfall of 580 mm in 28 hrs over 270 ha catchment causes ground flooding

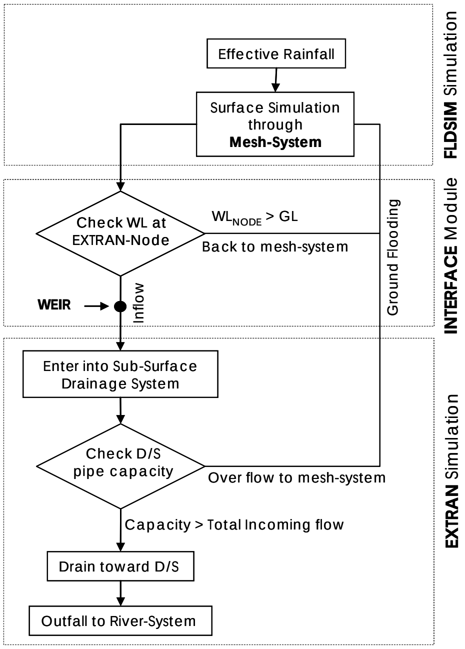


Fig.5 Working flowchart of the model

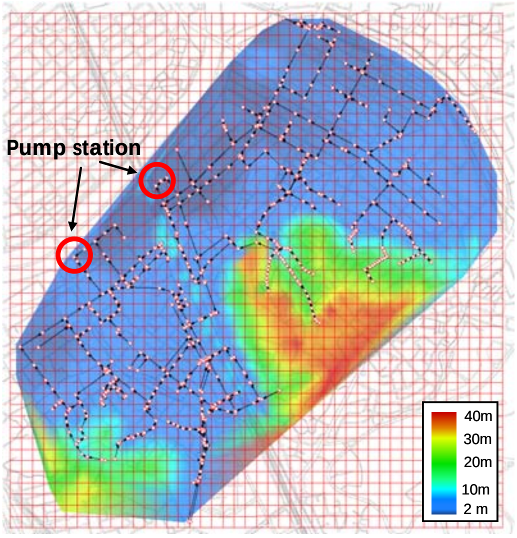


Fig.6 Layout of sewerage-network

Table 1. Overview of the major model elements

Model Element		Number	
		Case A	Case B
Surface System	Total active cell (mesh)	1085	1085
Subsurface System	Link	595	Nil
	Mesh-Node connection	312	
	Storage Basin	2	2
	Pump (Q_{total}=20.66 m^3/s)	4	4

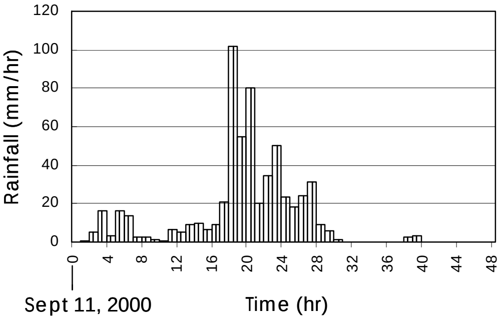


Fig.7 Rainfall over entire basin on September 11-12, 2000.

due to drainage congestion. Fig.8 shows the maximum flood extent obtained from the simulation of the integrated model (Case A). The simulated maximum flooding levels have been traced for several selected locations and printed on Fig.8 along with the available real flood marks to provide a general idea on how the simulated flood depths deviate from the real data. The figure shows a clear close agreement between the simulated flood depths and the observed flood marks. The time series flood depths for those selected locations are also shown in Fig.9. Close matching of model results and observed data ensures that the model was able to reproduce the actual flooding situation. The flood extents obtained from the other simulation (Case B) where the sewerage-network has been excluded is shown in Fig.10. Case B produces higher flood extents than the reality. Exclusion of sewerage-network in model underestimates the available drainage facilities of the site, and therefore, causes more water stored on ground. The less water has reached at pump station to be drained out to receiving body. Fig.11 shows the time series results of water pumped and stored in mesh-system in both cases. These findings clearly emphasise the necessity of using the integrated modeling approach to get a correct prediction of urban flooding.

CONCLUSION

An integrated model to simulate the urban flooding has been developed through a simultaneous coupling of 1D and 2D model. Virtual structures (weir or orifice) which substitute the inlet gratings of sewerage-system have been used as interface module to exchange the flow between 1D and 2D model. The model has been applied to simulate the flooding situation of Tenpaku-river basin, Nagoya, Japan. The basin experienced severe flooding on September 11, 2000 when a heavy rainfall (return period > 100 yr) occurred. The total rainfall of 580 mm in 28 hrs over 270 ha catchment causes ground flooding due to drainage congestion. The integrated modeling approach (Case A) where the sewerage-network (1D) and mesh-network (2D) have been coupled through virtual weirs produces accurate flood extent that shows a close agreement with the observed data. The other approach (Case B) using exactly the same drainage elements excluding the sewerage-network produces much higher flooding which can not be accepted as a reproduction of the real flood event. The present study ensures that the integrated modeling approach is the best option for a realistic and authentic reproduction of urban flood extents and therefore, the integrated modeling approach is highly recommended for any urban flood simulation.

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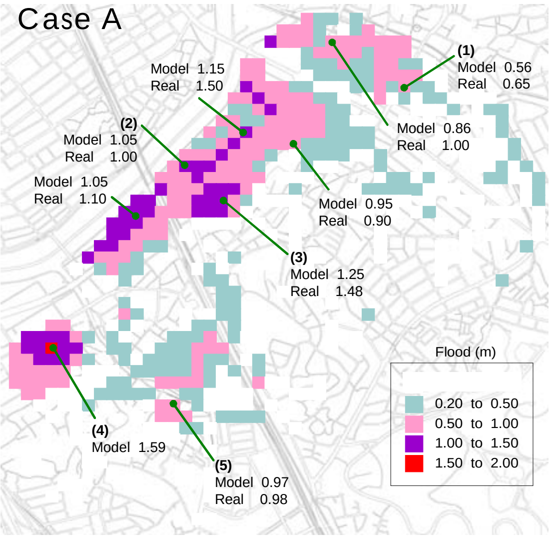

Fig.8 Maximum flood depth (Case A). Real flood marks are printed where available.

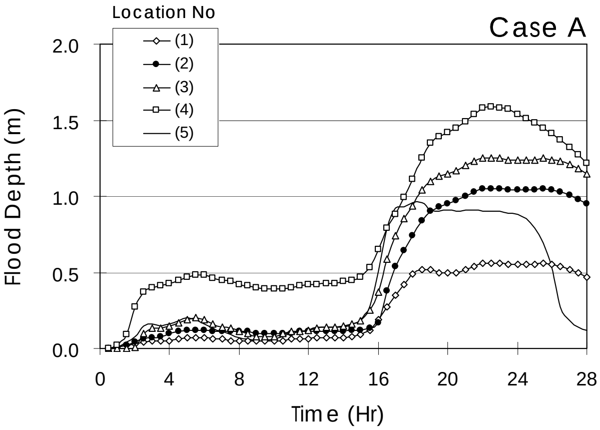

Fig.9 Time series flood depth at several selected locations (see Fig.8 for location index)

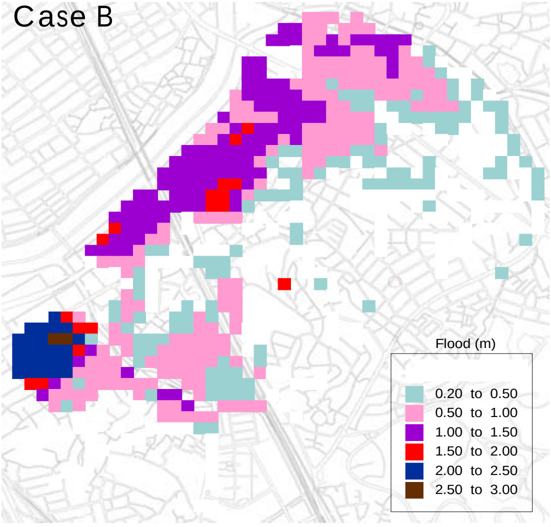

Fig.10 Maximum simulated flood depth where sewerage-network has not been considered (Case B)

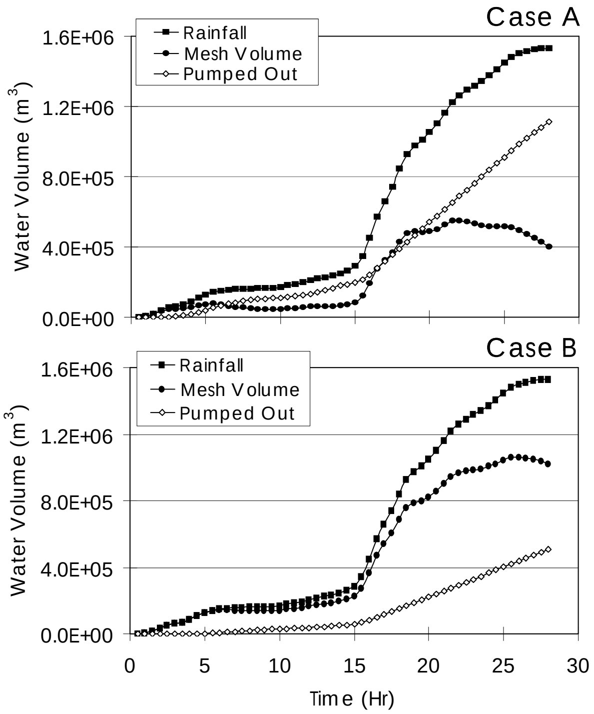

Fig.11 Time series mass balance (Case A and Case B)

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