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URBAN INUNDATION SIMULATION CONSIDERING ROAD NETWORK AND BUILDING CONFIGURATIONS

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ABSTRACT: The main difference between rural and urban area inundation is the existence of an impermeable layer and the complexity of the road and building configuration. Therefore, although surface overland flow can be appropriately simulated by the two-dimensional diffusive model in a rural area, there also is a need for a more accurate and elaborate simulation model. In this study, we simulated homogeneous and non-homogeneous mesh types to estimate the effect of road networks and building groups. Two-dimensional run-off flow model and one-dimensional slot-model simulated ground surface run-off flow and sewer pipe flow. To connect both models, we used a newly suggested bi-directional model and its coefficients (LEE et al., 2013). The simulated results showed a non-homogeneous case could calculate more reasonable results; the results further reveal the importance of using storm drains as exchange spots in the model.

Key Words: building and road network effects, sewerage system, storm drains, urban inundation

1. INTRODUCTION

Urban inundation due to climate change and torrential rainfall has been one of the most common natural disasters worldwide. For the case of rural areas such as agricultural fields, surface overland flow can be appropriately simulated by the two-dimensional diffusive model based on non-inertial surface flow dynamics (Hromadka and Lai, 1985; Wasantha Lal, 1998) because the surface overland flow processes are primarily determined by the topography, land cover, and soil type. However, in urbanized areas, the surface overland flow process is determined by artificial factors such as building configuration, road networks, and drainage systems (Hsu et al., 2000). Generally, overland flow direction is decided by gravity's direction along the road, but it can be changed by anthropogenic structures such as houses, buildings, and levees. Urban inundation can limit or completely obstruct the functioning of traffic systems and has indirect consequences such as loss of business and economic opportunities in addition to possible social consequences, the expected total direct and indirect losses are related to the physical properties of the inundation: depth, area, and duration.

The dual-drainage concept (Smith, 1993; Djordjević et al., 1999; Nasello and Tuciarelli, 2005) describes the bidirectional flow interactions between the ground surface and sewerage system. Much of the attention of flood inundation researchers has concentrated on benchmarking model codes against two-dimensional hydraulic models, including DIVAST, DIVASTTVD, TUFLOW, SIPSON and SWMM (Hunter et al., 2008).

There are two main reasons for urban inundation. The first is a lack of sewer system capacity, and the second is an insufficiency of storm drains (Lee et al., 2013). For instance, if the flow rate in a sewer pipe exceeds the maximum capacity of the pipe, the surface runoff flow will not drain into the sewer system through the storm drains and overflow may occur. On the other hand, if the flow rate does not exceed the maximum capacity, the surface flow can be captured and drained through the storm drain. Generally, it is somewhat difficult to imagine there may be an inundation in the latter, but it is possible. Although the designed capacity of a sewer system is enough to carry flooding discharge, if the discharge cannot be captured by the storm drains, ground surface inundation may occur (Hsu et al., 2000).

There are several techniques to consider the blockage effect of buildings in urban areas by using; (1) local friction-based representation of buildings; (2) the bottom elevation technique; and (3) vertical walls (Chen et al., 2008). McVillan and Basington (2007) have also tested the capabilities of building resistance, building blocks, building holes, and building porosity methods in urban inundation simulation and found the sub-grid treatment is needed for the parameterization of coarse grids in certain cases.

Our research group has been making an effort to develop an elaborate urban inundation model that can simulation run-off flow on the ground surface, the drainage process in a sewerage system and bi-directional interactions between the sewer system and the ground surface simultaneously. A number of models (SWMM, SIPSON, UIM etc.) have been proposed for urban inundation using the manhole as an exchange spot based on dual-drainage system because of numerical convenience. However, Lee et al., (2012; 2013) have emphasized the importance of storm drains as exchange spots of bi-directional interactions to approximate reality.

In this study, we distinguish between building groups and road networks; we artificially adjusted the elevation of both meshes to induce flows from build groups to road networks and the results with compared with a non-adjusted mesh case. We used a two-dimensional (2D) run-off flow model (Kawaike et al., 2002) and a one-dimensional model (1D) to simulate surface run-off and sewer pipe flow, respectively.

To evaluate the model applicability, we selected the Nakahama area of Osaka, Japan. We used rainfall data from 23 August, 2008 as a study case. The precipitation data and pumping station maximum capacities were the boundary conditions.

2. NUMERICAL MODEL

2.1 Mesh Generation

We obtained the GIS data of the road network was obtained from the Geospatial Information Authority of Japan (http://www.gsi.go.jp/index.html). We used 5m 5m Digital Elevation Model (DEM) data as the mesh elevation data. To generate unstructured triangular mesh, we employed the GID (11.0.5 version) software.

2.1.1 Ground Surface

Figure 1 and Figure 2 show homogeneous and non-homogeneous unstructured meshes, which represent road networks and building groups, respectively. We adjusted the road networks and building group meshes' elevation from their original values to -0.2m (to represent the curbs) and +20m (to represent building configurations), respectively.

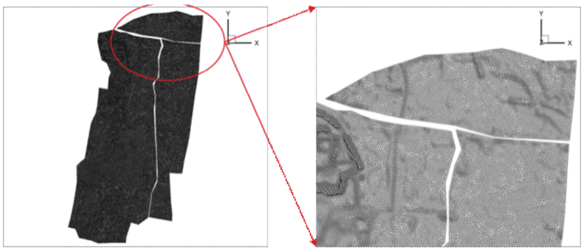


Figure 1: Homogeneous case (20m)

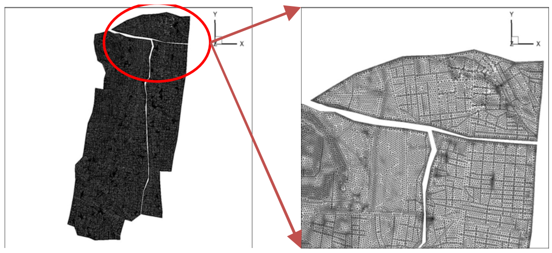


Figure 2: Non-homogeneous case (considering road networks and building groups)

Figure 3: Homogeneous case

Figure 4: Non-homogeneous case (considering road networks and building groups)

In this study, storm drains are bi-directional spots between the ground surface and the sewerage system. Generally, storm drains are of wide distribution on the road. Therefore, it is necessary to collect the distribution data of storm drains on the road to build a more realistic simulation model. However, the connecting works of storm drain distribution data are almost impossible because of the shape diversity, welter of storm drains, and time limitations.

We used two methods to generate storm drains in this study. We set all sewer pipes at 20m in all cases. We implemented mesh matching works between the ground surface and sewer pipe mesh using x and y coordination of both mesh data in a homogeneous case, because there was no information about the road. Each sewer pipe grid can find a perpendicular ground surface mesh through the matching works. If the center coordination of a sewer pipe grid is set within the ground surface mesh, the storm drain is set on the center of the ground surface mesh. On the other hand, storm drains are distributed on the road network grid and each storm drain searches for the nearest sewer pipe grid; we then collected connection information in a non-homogeneous case. The number of storm drains on the ground surface is adjusted based on a criterion (170m2/one storm drain) to avoid a non-equilibrium problem arising from a difference in the number of storm drains between the mesh generation methods.

2.1.2 Sewerage system

We obtained data about a total of 4,445 sewer pipes, 4,317 manholes, and 4 pumping stations. The data for each sewer pipe includes x and y coordinates, upstream and downstream connection data, and manhole shape, diameter size, elevation, and slope. Similarly, each manhole data entry includes x and y coordinates, elevation, bottom area, and connected pipe data. Therefore, it is possible to arrange all pipes and manholes with a pumping station. However, additional works are needed to trace all pipes and manholes to clarify the connection information because of data uncertainties.

As a result of data sorting, we rearranged 3,026 pipes and 2,903 manholes. The sewer pipe diameter ranged from 8.5m to 0.3m. Figure 3 and Figure 4 show sorted manholes and pipe data of homogeneous and non-homogeneous cases, respectively. There are 4 pumping stations. A blue circle indicates a pumping station; a red line is a sewer pipe; and black dots are storm drains.

2.2 Governing Equation

We used two kinds of flow models (2D run-off flow and 1D pipe flow) and interaction models (an exchange discharge model between the ground surface and sewer pipes, and an exchange discharge model between the manholes and sewer pipes) to simulate the study area. The run-off flow model used in this study consisted of a horizontal 2D inundation flow model (Kawaike et al., 2002) and a 1D slot model of sewer pipe flow (Chaudhry, 1979), while the interaction models were composed of the weir and orifice formula to calculate exchange discharge at the storm drains and the adjoining part between manholes and pipes (LEE et al., 2013).

2.2.1 2D Inundation Flow Model

The governing equations used for the 2D inundation flow model are as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=r_e-q_{ex} \quad [1]$$

$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (vM)}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{gn^2M\sqrt{u^2+v^2}}{h^{4/3}} \quad [2]$$

$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (vN)}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{gn^2N\sqrt{u^2+v^2}}{h^{4/3}} \quad [3]$$

where h is water depth; H is water elevation; u is x-direction water velocity; v is y-direction water velocity; M is uh (x-direction flux); N is vh (y-direction flux); r_e is effective rainfall; q_{ex} is the interaction discharge between the ground surface and sewer pipe; g is gravity acceleration; n is Manning's roughness coefficient; and t is time. Computational meshes are unstructured and triangular in shape; we adopted the Finite Difference Method.

2.2.2 1D sewerage system model

The 1D flow simulation with slot model simulated the flow within a sewer pipe. The governing equations are as follows:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_{ex} \quad [4]$$

$$\frac{\partial Q}{\partial t}+\alpha\frac{\partial (uQ)}{\partial x}=-gA\frac{\partial H_p}{\partial x}-gn^2\frac{|Q|Q}{R^{4/3}A} \quad [5]$$

where A is the wet area of the cross section; Q is flow discharge; q_{ex} is the lateral inflow discharge per unit of pipe length; α is a reduction factor of the convective acceleration term (Djordjević et al., 2004); u is velocity; R is hydraulic radius; and n is the roughness coefficient (we used n=0.012 for the sewer pipe in this study). H_p is the piezometric head ($H_p = Z_p + h$); Z_p is the bottom elevation of the sewer pipe; and h is water depth determined as follows:

$$h=\begin{cases} f(A) & : A \le A_s \\ D+(A-A_s)/B_s & : A > A_s \end{cases} \quad [6]$$

where f is a function of the relationship between water depth and wet area of the cross section of a circular pipe; A_s is the cross-sectional area of the sewer pipe; D is the pipe diameter; and B_s is slot width, determined as follows:

$$B_s=\frac{gA_s}{a^2} \quad [7]$$

10.0*m/s* represented the pressure wave speed *a* of the sewer pipe.

The manhole continuity equation can be written as:

$$\frac{\partial h_m}{\partial t} = \frac{\sum_{i=1}^{M} Q_i}{A_m} \qquad [8]$$

where h_m is the water depth of the manhole; Q_i is the exchange discharge between the manhole and connected pipes and manhole; and M is number of the connected pipes.

The water depth of pumping station is calculated as:

$$\frac{\partial h_{pm}}{\partial t} = \frac{Q_{pm}}{A_{pm}} \qquad [9]$$

where h_{pm} is the pumping station water depth; Q_{pm} is the drainage capacity of the pumping station; and A_{pm} is the bottom area of pumping station.

2.2.3 Interaction model

There are two interaction models: between the manhole and sewer pipe, and between ground surface and sewer pipe, to calculate exchange discharges.

Manhole and sewer pipe

- In the case of $h_s \geq h_m$

If ($h_m / h_s \geq 2/3$)

$$Q = 0.35 \times A_s \sqrt{2gh_s} \qquad [10]$$

If ($h_m / h_s < 2/3$)

$$Q = 0.91 \times A_m \sqrt{2g(h_s - h_m)} \qquad [11]$$

- In the case of $h_m \geq h_s$

If ($h_s / h_m \geq 2/3$)

$$Q = -0.35 \times A_m \sqrt{2gh_m} \qquad [12]$$

If ($h_s / h_m < 2/3$)

$$Q = -0.91 \times A_s \sqrt{2g(h_m - h_s)} \qquad [13]$$

where A_s is the wetted cross-section area of the sewer pipe; and A_m is the virtual cross-section of the manhole.

Ground surface – sewer pipe

- Inlet flow

If, $(h_{hs} - h_{hg}) / B_0 \geq 0.5$

$$Q = C_{do} \times A_{sd} \sqrt{2g(h_{hs} - h_{hg})} \quad [14]$$

If, $(h_{hs} - h_{hg}) / B_0 < 0.5$

$$Q = C_{dw} \times L \times \frac{2}{3} \sqrt{2g} (h_{hs} - h_{hg})^{\frac{3}{2}} \quad [15]$$

- Overflow

If, $(h_{hg} - h_{hs}) / B_0 \geq 0.5$

$$Q = -C_{do} \times A_{sd} \sqrt{2g(h_{hg} - h_{hs})} \quad [16]$$

If, $(h_{hg} - h_{hs}) / B_0 < 0.5$

$$Q = -C_{dw} \times L \times \frac{2}{3} \sqrt{2g} (h_{hg} - h_{hs})^{\frac{3}{2}} \quad [17]$$

where C_{do} is the orifice coefficient; C_{dw} is the weir coefficient; h_{hs} is the piezometric head of the sewer pipe; h_{hg} is the water depth on the ground surface; A_{sd} is the storm drain area; L is the perimeter of the storm drain; and B_0 is smallest width of the storm drain.

Figure 5 shows the calculation process of the model. Rainfall data was the input data, and the outlet boundary conditions were the maximum capacities of the pumping stations.

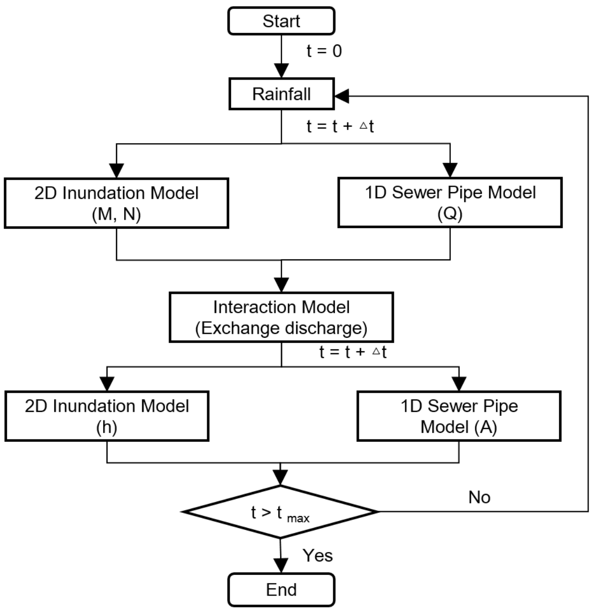


Figure 5: Flow chart of the calculation process of the model

3. MODEL APPLICATION

We carried out simulations for the recent severe urban flooding in the Nakahama area of Osaka, Japan on 23 August 2008. The study area was approximately 18.1km^2. We compared two study cases to estimate the effect of road networks and building configuration. Figure 6 shows precipitation data from the Osaka observatory station records. Figure 7 shows the maximum capacities of the outlet pumping stations. The rainfall duration was approximately 3 hours (the rainfall intensity was 76.5mm during 1 hour). The simulation started at 14:30, 23 August, 2008 in real time, and ended at 00:30, 24 August, 2008, encompassing 10 hours to confirm the drainage process. This study did not include infiltration and river flow effects.

Figure 8 and Figure 9 show the simulation results and a comparison between homogeneous and non-homogeneous mesh cases. Both cases show similar inundation propagation tendency from the left side to the right side because the elevation of left side is higher than right side. Inundation started at 15:36 23 August, and the maximum inundation depth was recorded at 16:43. However the inundation areas were different in both cases. Figure 10 shows the time variation in the inundation depth. In both cases, the peak time of inundation was similar, but the inundation areas of homogeneous case were larger than the non-homogeneous case.

Table 1 summarizes the time variation of the inundation area according to the inundation depth. The mesh size of the homogeneous case was larger than the non-homogeneous case. Therefore, the homogeneous case may have a wider inundation area under the same conditions because the surface run-off flow can distribute on a mesh without disturbance of building configuration. Also there is no tipping effect of the run-off flow caused by road and curb.

Similarly, the total volume of stored water should be the same if the sewerage system, including storm drains, has the same capacity. We can easily check the amount of stored water on the ground by depth multiplied by area. However, stored water volume also showed the homogeneous case was higher than the non-homogeneous case. This phenomenon can be explained by the effective distribution of storm drains.

Storm drains are distributed on the ground mesh vertically above the sewer pipe grid in the homogeneous case, while storm drains are distributed along the road networks in the non-homogeneous case. Also, we reduced the elevation of road network meshes 20cm to represent the curb that divides the road from other areas in an urban area. Generally, road networks are appropriately designed to carry storm water. Run-off flow should accumulate on the road and is captured by storm drain. In the homogeneous case, the storm drains are not distributed on the road.

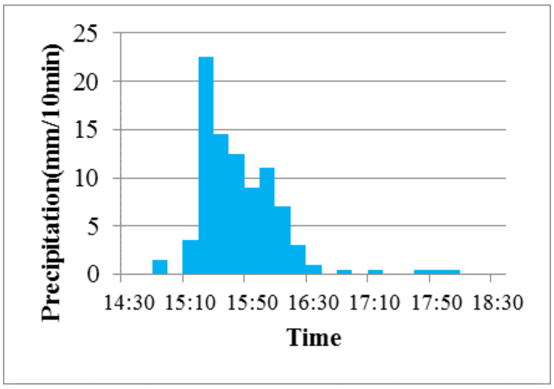


Figure. 6 Precipitation data

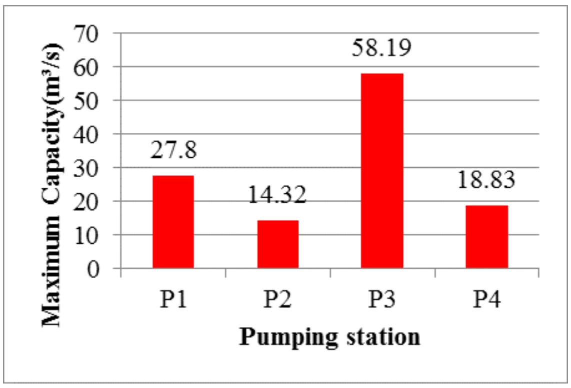
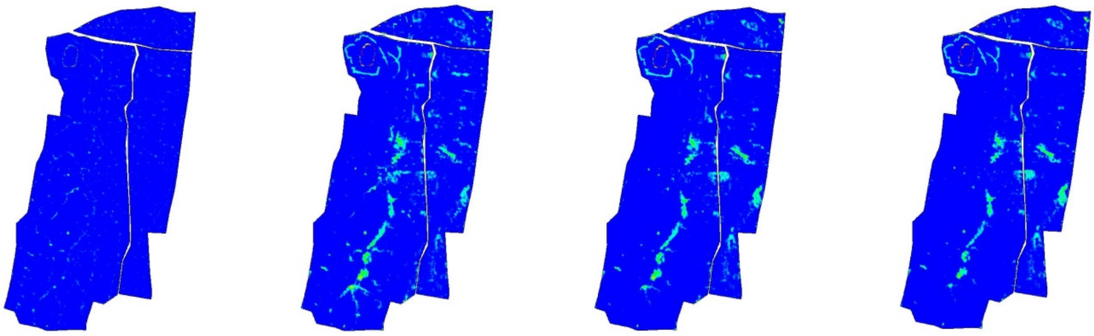
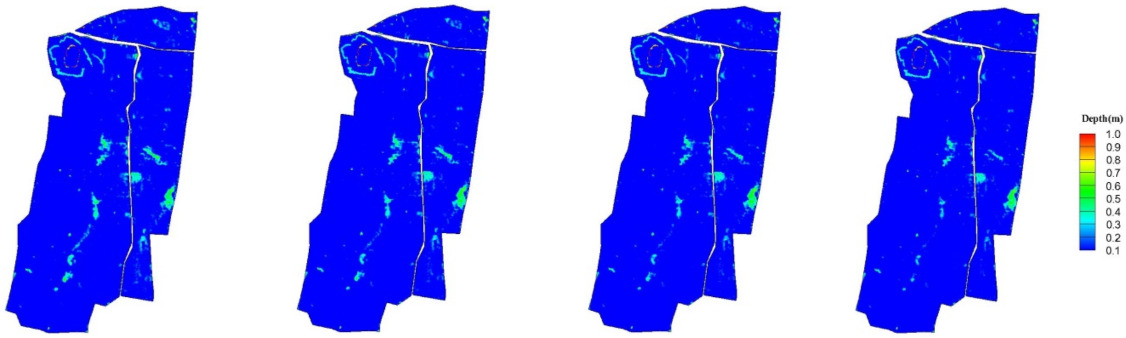


Figure. 7 Maximum capacity of pumping stations

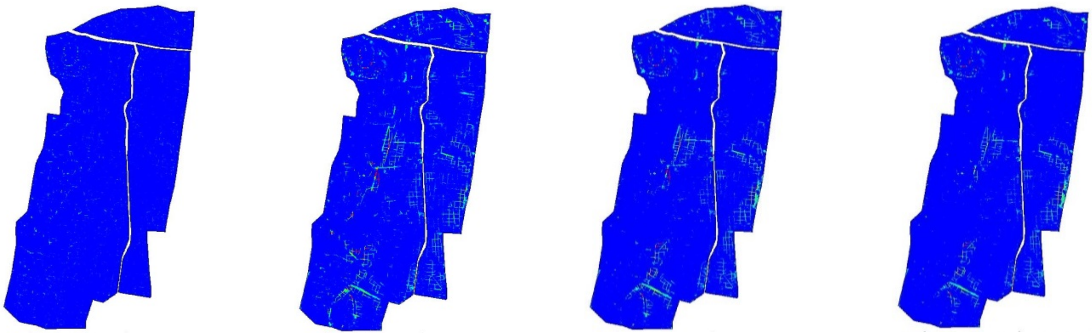


(a) Time = 15:36 (b) Time = 16:43 (c) Time = 17:50 (d) Time = 18:40

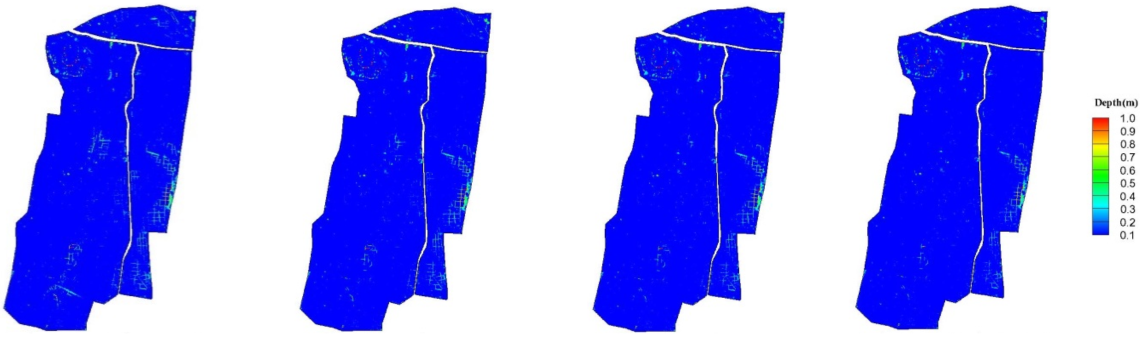


(e) Time = 20:03 (f) Time = 21:26 (g) Time = 22:50 (h) Time = 00:30

Figure 8: simulation results of homogeneous mesh case



(a) Time = 15:36 (b) Time = 16:43 (c) Time = 17:50 (d) Time = 18:40



(e) Time = 20:03 (f) Time = 21:26 (g) Time = 22:50 (h) Time = 00:30

Figure 9: simulation results of non-homogeneous mesh case

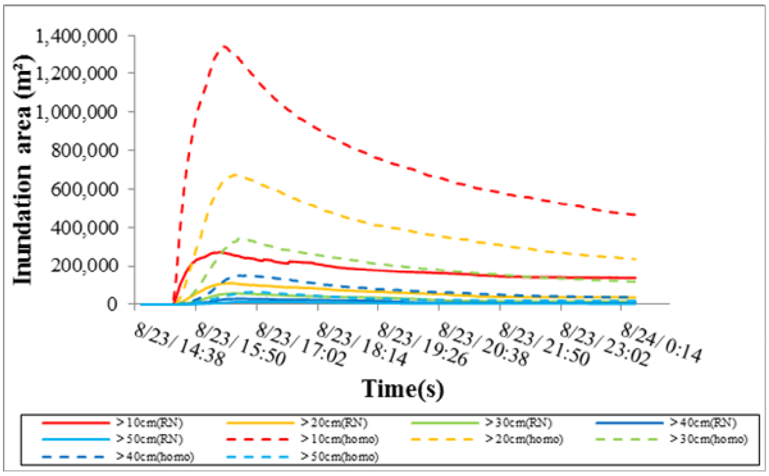


Figure 10: Time variation of inundation depth

Table 1. Comparison of peak inundation depth

Index(peak depth)		> 10cm	> 20cm	> 30cm	> 40cm	> 50cm
Area(m^2)	homo	1,340,370.7	672,648.4	343,855.2	145,494.5	63,255.1
	non-homo	271,063.4	109,038.3	56,926.8	28,784.0	13,378.1
Total volume (m^3)	homo	134037.07	134529.68	103156.56	58197.8	31627.55
	non-homo	27106.34	21807.66	17078.04	11513.6	6689.05
Ratio(homo/non-homo)		4.9	6.2	6.0	5.1	4.7

4. CONCLUSION

In this study, we used two different kinds of to estimate the importance of considering the road network and storm drains in an urban inundation simulation. The first mesh was a homogeneous type. The second mesh considered road networks and building groups. Both meshes used the same 5m×5m DEM data. In the homogeneous case, we only used average DEM elevation values for the mesh elevation. However we artificially adjusted the road network (-0.2m) and building group (-20m) meshes to represent their properties.

We selected the Nakahama area of Osaka, Japan as study area. The precipitation event of 23 August, 2008 was the selected study case. The duration of the rainfall was about 1 hour, but the simulation covered 10 hours to confirm the drainage process.

A 2D run-off flow model and a 1D slot model simulated the surface run-off and sewer pipe flow, respectively. We set the storm drains as the exchange discharge spot between the ground surface and sewerage system. Although both simulation results showed a similar propagation tendency of the inundation area, the total volume of stored water and inundation areas on the ground calculated indicated the homogeneous case was larger and wider than the non-homogeneous case.

The drainage process was not well simulated in the homogeneous case. Therefore, the selection of the exchange discharge spot is very important in urban inundation simulation. Distributing the storm drains on the road could be a good choice.

Unfortunately, we could not obtain the inundation survey data. It was thus impossible to compare our results with realistic data. Therefore, the model’s applicability must be validated by survey data in the next study.

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