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Numerical Assessment of On-Site Storage Facilities to Mitigate Pluvial Inundation Damage in Urban Area

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Abstract

On-site storage facilities are an effective countermeasure for mitigating the damage caused by pluvial inundations in urban areas. In this study, we slightly modified our previously-developed integrated simulation model for pluvial inundation, and applied it to an actual urban area. We quantitatively evaluated the mitigation effects of assumed on-site storage facilities, and found that as a single strategy, on-site storage facilities with a practical scale of storage capacity could not provide sufficient mitigation. We recommend installing both on-site and off-site storage facilities widely distributed in a catchment area.

Keywords: urban inundation, torrential rainfall, sewerage system, on-site storage facilities

1. INTRODUCTION

In Japan, inundation disasters frequently occur, particularly in urban areas. These disasters are caused by local torrential rainfall. Stormwater drainage systems of sewer pipe networks are intended to play an important role in preventing such inundation disasters. However, when the rainfall intensity exceeds the capacity of the drainage system, the system overflows and sewerage is discharged on the surface. In some cases, this inundation is caused by a loss of inherent infiltration and retention functions in the catchment area, due to its development and cover with impermeable surface materials. Therefore, the construction of stormwater storage facilities to restore these functions to a catchment area is an effective countermeasure against pluvial inundation. There are two types of storage facilities: off-site and on-site. In off-site storage, such as retarding basins and regulating ponds, stormwater propagating away from remote locations is stored via rivers or sewer pipes. In contrast, in on-site storage facilities (for instance, small tanks installed in homes, school yards, or playgrounds), stormwater is immediately collected and stored on-site. However, because of the high construction costs and the fact that the ability of these on-site facilities to mitigate damage during inundation disasters is unclear, adequate storage facilities have not been installed in urban areas.

Numerical simulations are an effective tool for analyzing the mitigation effects of on-site storage facilities. Many simulation models for urban pluvial inundation have been developed and applied to actual urban areas (e.g. Chen et al., 2007; Leandro et al., 2009). Most of these models consist of a two-dimensional (2D) model for surface inundation, a one-dimensional (1D) model for sewer pipe flow, and an interaction model connecting surface inundation and pipe flow. However, most of those studies were aimed at developing simulation models and reproducing past rainfall event phenomena, and the developed models have rarely been used to estimate the mitigation effects of countermeasures.

Our research group has been developing an integrated simulation model of urban inundation, consisting of a 2D model, a 1D model, and an interaction model using weir and orifice equations (Lee et al., 2013; Bazin et al., 2014). The model has been applied to actual urban areas in Japan using detailed topography and pipe network data (Lee et al., 2016; Kawaike et al., 2016). The developed model has been used to evaluate the mitigation effects of off-site storage facilities in simulations applied to Osaka (Ko et al., 2018).

In this study, we performed several simulations using the assumption that on-site stormwater storage facilities are installed at single-family housing and apartment housing, etc., to assess whether such facilities can effectively mitigate against inundation damage. Thus, the purpose of this study is to quantitatively evaluate the effects of on-site storage facilities against pluvial inundation damage.

2. NUMERICAL MODEL

2.1 Integrated model for pluvial inundation

To simulate inundation flow in this study, we employed our pluvial inundation model, which consists of a 2D model of overland inundation flow, a 1D model of sewer pipe flow, and an interaction model based on the weir and orifice equations (Lee et al., 2013; Lee et al., 2016).
This model assumes that overland stormwater flows either drain into sewer pipes or overflow sewer pipes through storm drains at every street mesh.

2.2 Treatment of buildings

In our previous model, computational meshes in the building category had sufficiently high elevations, and the stormwater present on that mesh flowed by gravity across the ground surface according to the elevation difference, without any special treatment. Additionally, the high elevations prevented the building interiors from flooding.

In this study, we improve the treatment of buildings in the model. For the mesh elevations in the building category, we adopted elevation data calculated from a 5-m resolution digital elevation map published by the Geospatial Information Authority of Japan. We assumed that depending on the proportion of the building roof area, part of the stormwater present on those meshes flows directly into the sewer pipes via the shortest distance from the building mesh centroid. Here, we need to consider the arrival time from the building to the pipe. In this study, we assume that the propagating velocity of the stormwater is 1.0 m/s. The stormwater laterally flows into the pipe with a time lag derived from the propagating distance and assumed propagating velocity.

Building interiors are not completely water-proof. In actual events, inundation water intrudes into buildings. In this study, we introduced intrusion parameter β at the boundaries between the building meshes and other meshes. Intrusion parameter β is defined as the opening ratio of possible length for inundation water exchange to the mesh boundary length, which regulates the flow exchange between streets and residential blocks. The inflow discharged into the building is restricted by multiplying the intrusion parameter (β) by the flow flux. The adopted value of intrusion parameter β is described later.

The treatment of buildings in this study is illustrated in **Fig. 1**.

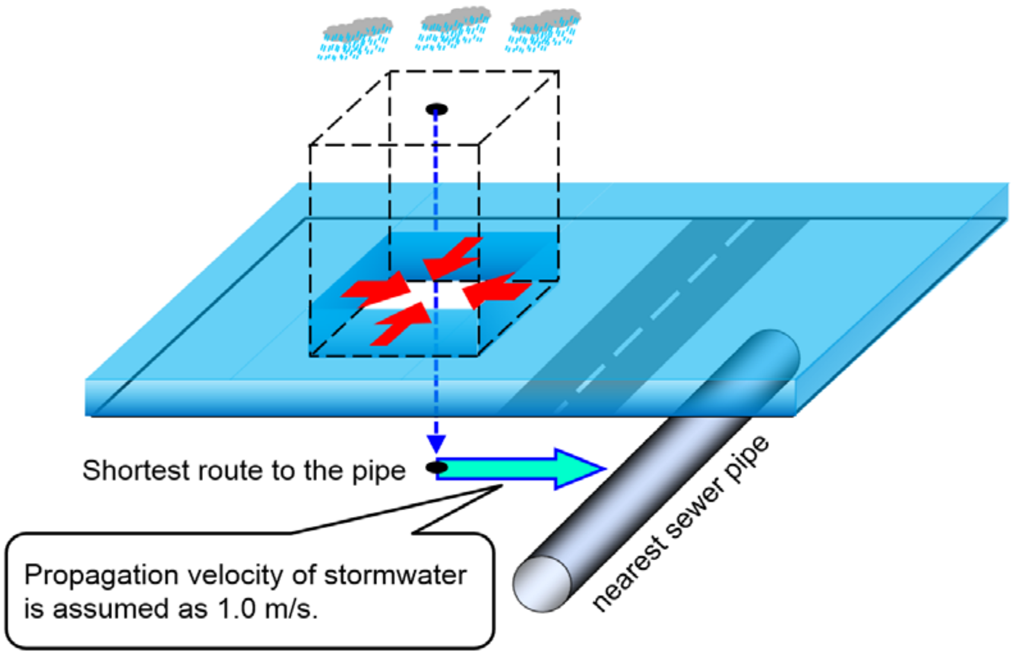


Fig. 1 Treatment of buildings

3. APPLICATION TO AN ACTUAL URBAN AREA

3.1 Target area

The target of this study is a sewerage catchment area in Osaka City: Nakahama Treatment Area. **Figure 2** shows the target area and its location. Nakahama Treatment Area is located on the eastern side of Uemachi high-land, which has an area of 18.1 km^2 and a population of 300,000. Nakahama Treatment Area was selected because its delineation is relatively easy —— surrounded by Uemachi high-land, Neya River, and Hiranogawa Diversion Channel. We have applied our model to this area several times (Lee et al., 2016; Ko et al., 2018).

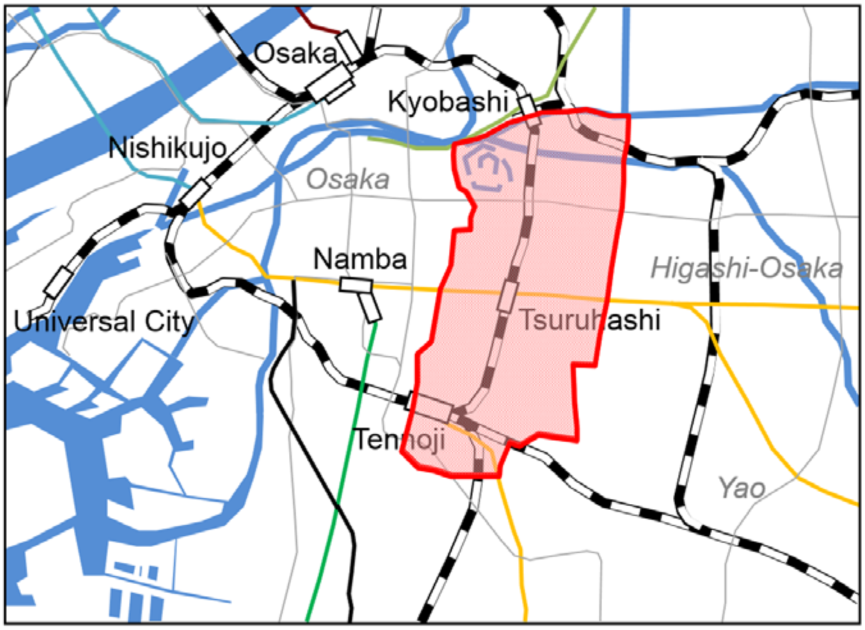
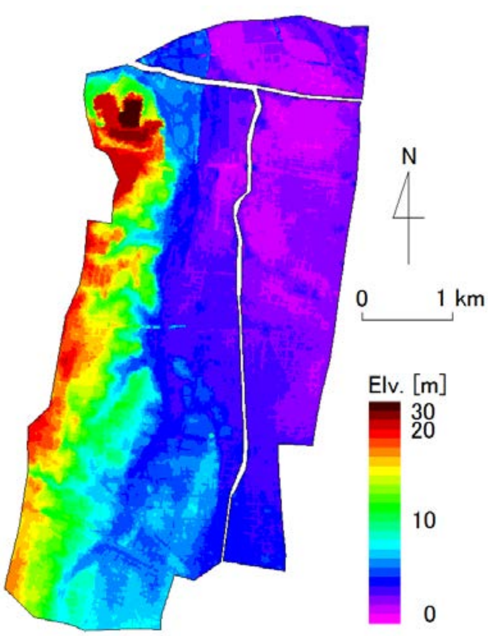


Fig. 2 Target area

This target area was divided into 109,034 unstructured triangular meshes. The mean size of those meshes is approximately 20 m. However, in some regions, much finer meshes 2 m in size are adopted. Those computational meshes are categorized as single-family housing, apartment housing, offices, schools, playgrounds, streets, and others. **Figures 3** and **4** show the surface elevations and categories of the computational meshes, respectively.



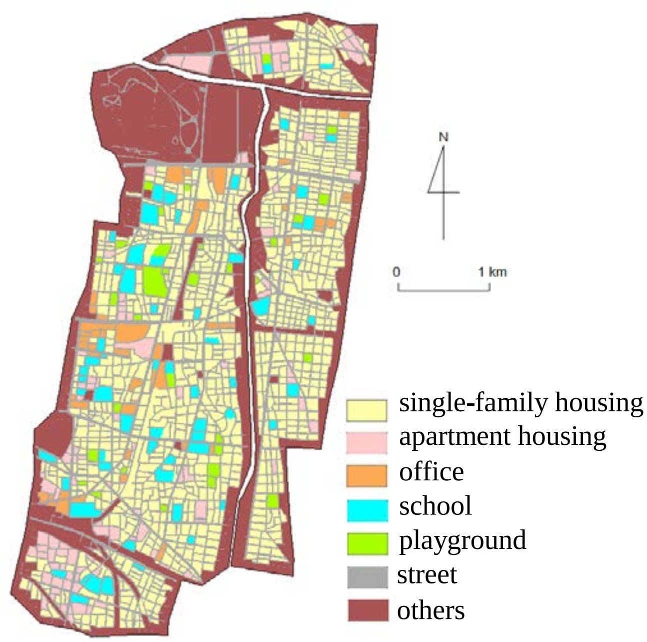


Fig. 3 Surface elevation

Fig. 4 Mesh categories

Sewer pipes with diameters greater than 600 mm and the manholes connected to those pipes are adopted in the simulation. In this study we considered 4,445 sewer pipes and 4,317 manholes. In Osaka City, because of low elevation of the residential area, compulsory drainage from the downstream end of the sewer pipe network with pumps is necessary. Five pumping stations are located in the target area, and their drainage effects are considered in the simulation. However, the water level of the external rivers is neglected. **Figure 5** shows the sewer pipes, manholes, and pumping stations used in this study. Overall, the sewer pipes flow from south to north, and their outlets and pumping stations are concentrated in the northern part of the target area.

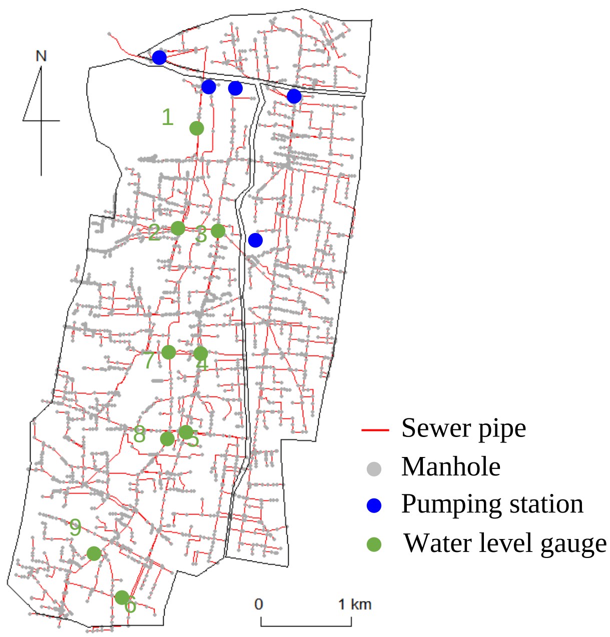
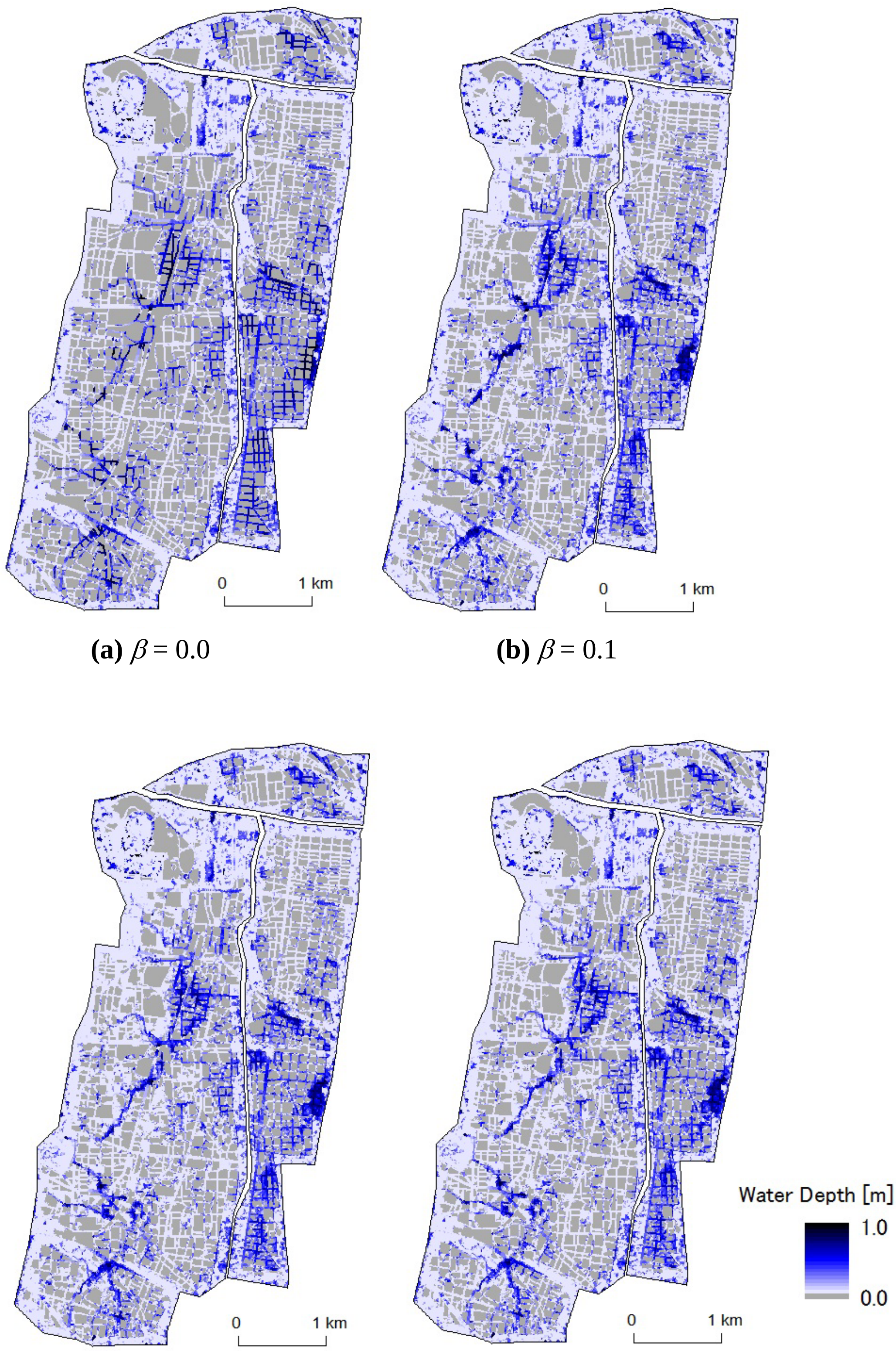


Fig. 5 Sewer pipes, manholes, and pumping stations

3.2 Intrusion parameter

In the simulation, the value of intrusion parameter β (described in **2.2**) must be determined. However, it is very difficult to convert the detailed building configuration data into an intrusion parameter at each mesh boundary. Therefore, as we describe in this section, we uniformly set the intrusion parameter to four different values (β = 0.0, 0.001, 0.01, and 0.1) and compared the results. **Figure 6 (a) – (d)** shows the maximum inundation depth with different intrusion parameter values. We use rainfall data observed at five rain gauges around the target area on August 25, 2013. During this rainfall event, 27.5 mm rainfall was observed at Osaka Regional Headquarters, JMA, which broke their highest record of 10-minute precipitation and resulted in more than 500 houses being inundated. The hourly and daily precipitations were 49.0 mm and 88.5 mm, respectively. For β = 0.0 (**Fig. 6 (a)**), the inundated area is restricted along the streets, and high water depths are found. On the other hand, for β = 0.001, 0.01, and 0.1 (**Fig. 6 (b)**, **(c)**, and **(d)**), inundation occurs in almost the same places as the case of β = 0.0, and the inundated area is slightly larger with lower water depths. However, we did not observe significant differences in water depths among these three cases.



(a) $\beta = 0.0$ **(b)** $\beta = 0.1$

(c) $\beta = 0.01$ **(d)** $\beta = 0.001$

Fig. 6 Maximum inundation depth using different intrusion parameters

Because there is no validation data for overland inundation in this area, we cannot determine the value of β quantitatively here. For the next section, intrusion parameter β is set to 0.01 as the most probable value of the opening ratio in a highly urbanized area. In the simulations of the next section, intrusion parameter β will affect inundation flow on the overland surface after the stormwater is cut off at the on-site storage.

3.3 Validation of sewer pipe model

The water levels at the nine manholes indicated in **Fig. 5** were measured during the short-term rainfall event on August 25, 2013. **Figure 7** shows a comparison between the measured and calculated water levels at the nine manholes. We found that the water level peak and fluctuating trends could be calculated at many manholes, although some numerical instabilities and water level overestimations were found at several of the manholes. The difference of the initial water level and overestimation might be caused by some problems of replication of the rainfall distribution or the actual pipe connection on the simulation data. Numerical fluctuations are found at Water Level Gauges 1, 2, and 3 affected by compulsory water removal at the pumping stations and the slot model applied to the sewerage system simulation. Consequently, the simulation results of this model are acceptable for urban pluvial inundation.

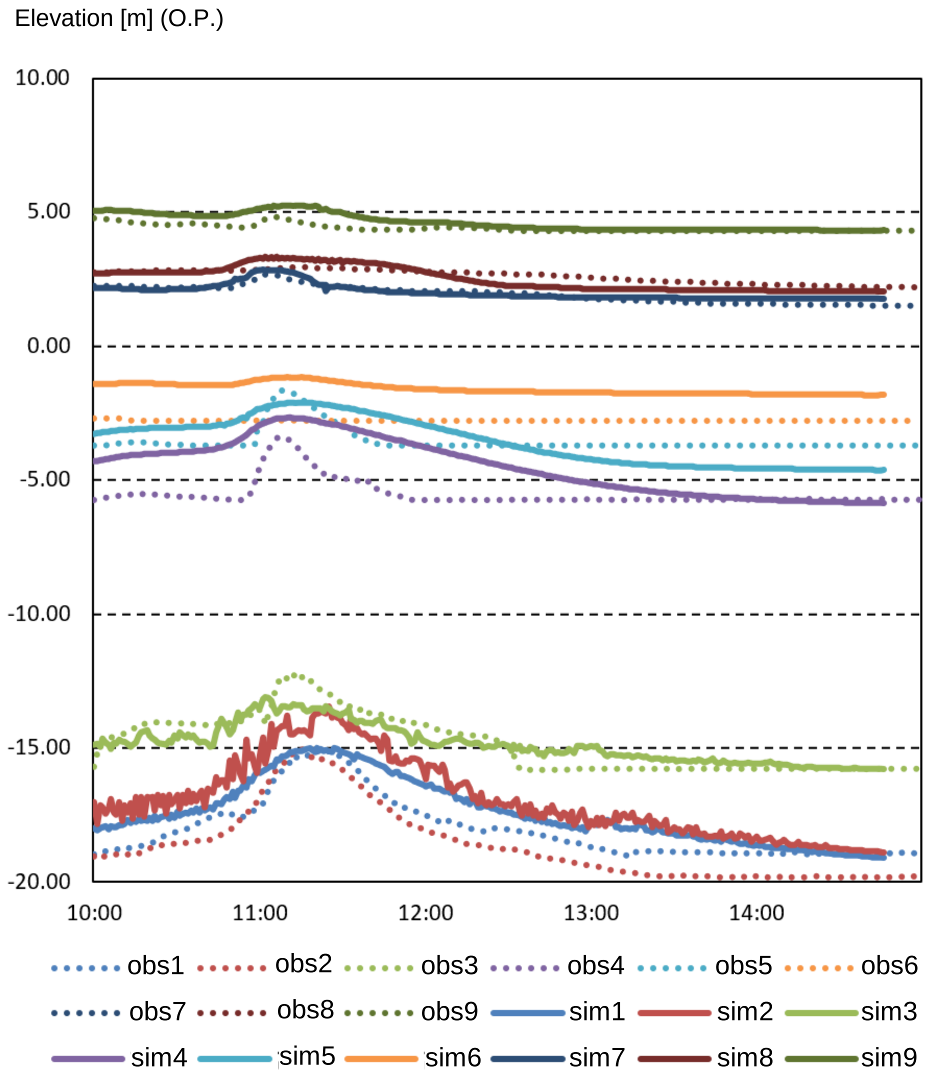


Fig. 7 Comparison between observed and simulated water levels at nine manholes

4. MITIGATION EFFECTS OF ON-SITE STORAGE FACILITIES

4.1 Simulation conditions

Osaka City experienced short-term torrential rainfall events in 2011, 2012, and 2013. Pluvial inundation occurred in some locations in our target area, the Nakahama Treatment Area. In this study, as countermeasures against such pluvial inundation, we assumed that small-scale on-site storage facilities were installed in the target area.

According to the mesh categories indicated in **Fig. 4**, the following storage capacities are assumed in each mesh. The standard values for possible storage area and maximum storage depth are described in the official guidelines (Association for Rainwater Storage and Infiltration Technology, 2007).

Single-family housing

The roof area occupies 90% of the mesh area, and one single-family housing accounts for 70 m^2. A storage capacity of 1 m^3 is attached to each individual house. The stormwater catchment area is equivalent to the roof area.

Apartment housing

The roof area occupies 60% of the mesh area, and the remaining 40% is used for parking lots, etc. Assuming a sufficiently large amount of storage capacity, all of the stormwater present on the roof is stored. In other areas (parking lot, etc.), storage on the ground surface is considered; the possible storage mesh area of 84% and a maximum storage depth of 10 cm. The catchment area of the stormwater is equivalent to the parking lot area.

Offices

The roof area occupies 60% of the mesh area, and all of the stormwater present on the roof is stored. Storage on the ground surface is not considered here, which means that the stormwater present in the other 40% of the area is not stored, and flows on the surface as inundation water.

Schools

The school building roof area occupies 30% of the mesh area, and the remaining 70% is used for the school yard. All of the stormwater present on the school building roof is stored. Storage on the ground surface is considered for the school yard; a possible storage mesh area of 40% and a maximum storage depth of 30 cm. The stormwater catchment area is equivalent to the school yard area.

Playgrounds

The ground surface provides a possible storage mesh area of 60% and a maximum storage depth of 20 cm. The stormwater catchment area is equivalent to the entire mesh area.

In the simulation, the above proportions of the roof area and surface area are assumed in each computational mesh. The rainfall is given on each mesh, with a runoff ratio of 0.9, and some part of the rainfall amount is stored in the storage facilities, depending on the residual storage capacity of each mesh. If the mesh has no residual storage capacity, the rainfall is given on the surface as the inundation water.

We set the following three cases for storage capacities: no storage facilities (Case 0), the capacity of storage facilities (Case 1), and the case where only the single-family housing meshes were provided with five-fold capacity (Case 2). The storage capacity of each category is summarized in **Table 1**. Case 1 can be regarded as a feasible goal for implementing on-site storage facilities. Case 2 would be difficult to implement using only on-site storage facilities, but can be considered to be a goal for total storage capacity, including alterative off-site storage facilities used to significantly mitigate pluvial inundation damage.

Table 1 Storage capacity allocated to each mesh category (unit: m^3)

	Case 0	Case 1	Case 2
Single-family housing	0	87,309	436,543
Apartment housing	0	29,577	29,577
Office	0	0	0
School	0	72,253	72,253
Playground	0	42,042	42,042
Total	0	231,181	580,415

(The roof storage capacity is not included except for individual houses)

The rainfall used in this simulation is a central peaked hyetograph with a return period of 10 years. The rainfall duration time is set as 2 h, because torrential rainfall was concentrated in a period of only 1 or 2 h for the events observed in Osaka City on August 27, 2011; August 18, 2012; and August 25, 2013. **Figure 8** shows the hyetograph used in this simulation, derived from the following rainfall intensity equation (1) for Osaka City.

$$r = \frac{999}{t^{2/3}+4.81} \tag{1}$$

The total rainfall amounts for 1 and 2 h are 49.6 mm and 68.6 mm, respectively.

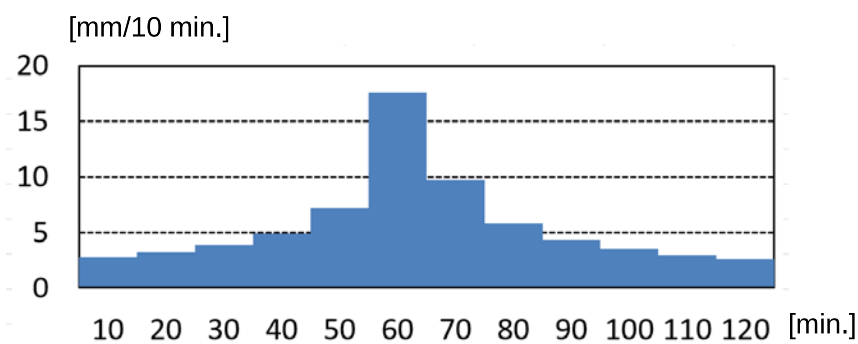
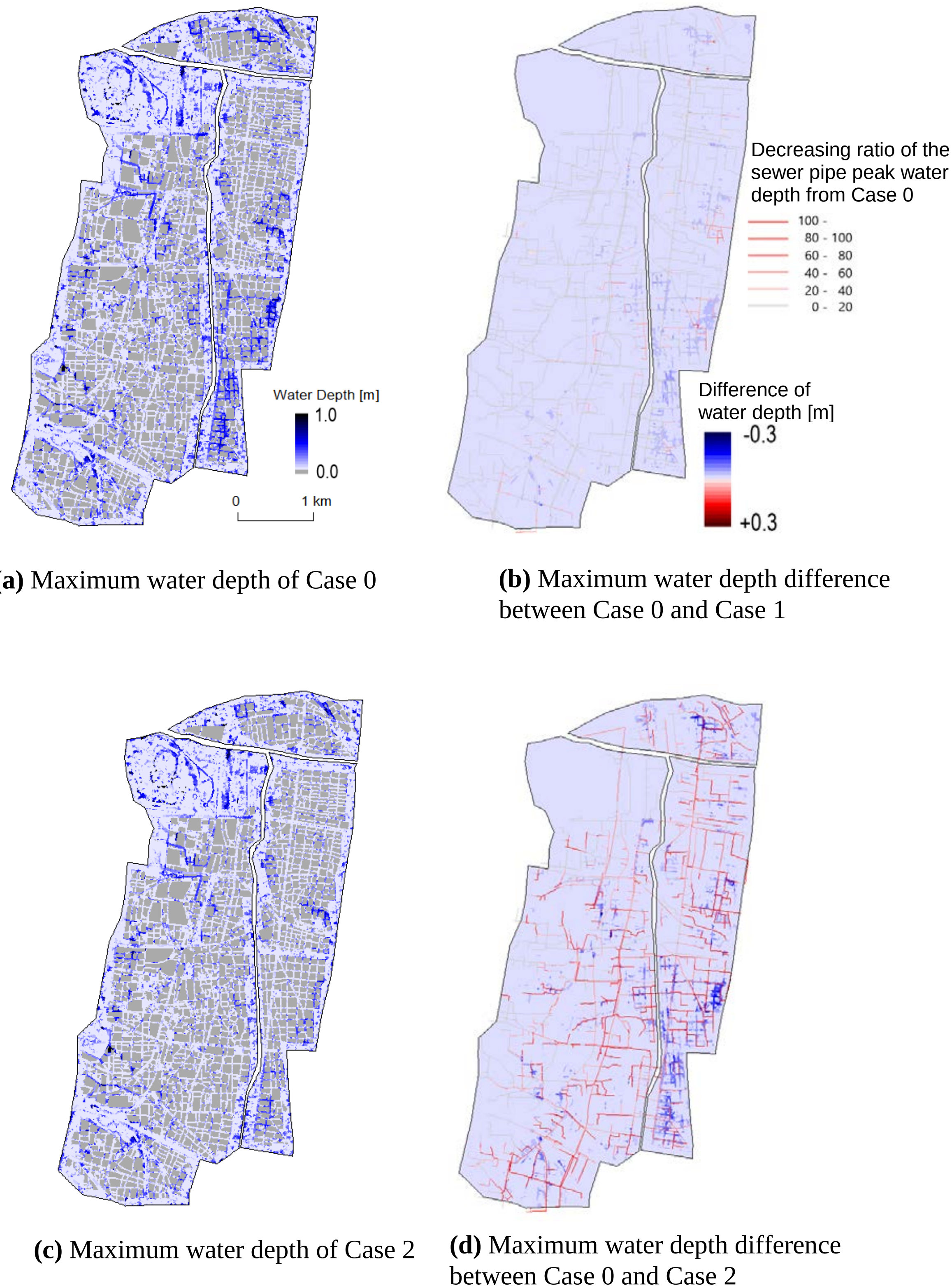


Fig. 8 Hyetograph of the model precipitation



(a) Maximum water depth of Case 0

(b) Maximum water depth difference between Case 0 and Case 1

(c) Maximum water depth of Case 2

(d) Maximum water depth difference between Case 0 and Case 2

Fig. 9 The maximum water depth of Case 0 and mitigation effects of on-site storage facilities

4.2 Mitigation effects of on-site storage facilities against pluvial inundation

Figure 9 (a) shows the maximum water depth for Case 0. The inundated areas are widely spread because the rainfall intensity used here is almost equivalent to that observed on August 25, 2013, which exceeded the sewerage system capacity. Along streets with low elevations, several areas experienced water depths greater than 0.5 m maximum. **Figure 9 (b)** shows the difference in maximum water depths between the case with no storage capacity (Case 0) and the case with storage capacity (Case 1). Based on these differences, the mitigation effects of on-site storage facilities were small, although small decreases in water depths were found in a very few number of areas. **Figure 9 (b)** also shows the decreasing ratio of sewer pipe peak water depth from that of Case 0. Additionally, the figure shows that the decreasing effects of sewer pipe water depth are also small. In this simulation, while the storage at large apartment complexes, offices, schools, and playgrounds still remained vacant capacity, the storage capacity of single-family housing was full of stormwater at an early stage. Therefore, the storage capacity shown in **Table 1** is not sufficient for the amount of precipitation modeled, and the total capacity should be increased, particularly for the single-family housing, which occupying the majority of the target area.

With reference to a similar numerical study by Nakagawa et al. (2004), although the simulation conditions such as the rainfall pattern, the land use, and the capacity of assumed on-site storage facilities are different from those in our simulation, they also concluded that the mitigation effects of storage facilities are limited if the assumed storage capacity is not sufficient for the total rainfall amount. However, even in those cases, the inundated area with a depth of more than 20 cm decreased to some extent from the case with no storage, which is different from our results and requires further investigation.

Figure 9 (c) and **(d)** show the maximum water depth for Case 2 and the difference in maximum water depth between the case without storage capacity (Case 0) and the case with five-fold storage capacity in the single-family housing meshes (Case 2), respectively. From these figures, we can observe that the water depths decrease significantly, particularly in areas with low elevations and relatively high water depths (as in Case 0). The areas in which the water depths decreased are much more widely found in this simulation than those of Ko et al., (2018) who implemented a single large storage tank with a capacity of 50,000 m^3, attached to a sewer pipe. From **Fig. 9 (d)**, we can see that the water depths in the sewer pipes decrease in many locations from the upstream to the downstream area, which might help to decrease overland inundation depths. Consequently, if the storage capacity is widely and sufficiently distributed in the catchment area, inflow discharges into the sewerage system are decreased, as are inundation depths on the ground surface.

5. CONCLUSIONS

Using an integrated model for pluvial inundation, we aimed to quantitatively evaluate the mitigation effects of assumed on-site storage facilities. We found that the practical on-site storage capacity for a single-family home (1 m^3) does not provide sufficient mitigation. Additionally, the effects of storage at large apartment complexes, offices, schools, and playgrounds are limited for model precipitation with a 10-year return period. Overland inundation depths decreased significantly when five-fold storage volume was provided to single-family housing (single-family housing occupied most of the target area). The effects of such on-site storage facilities, which were widely and sufficiently distributed in the overall catchment area, were found in many places. In contrast, the effects of off-site storage were locally found just around the facility. In the next step of our research, we will investigate the mitigation effects provided by the simultaneous installation of on-site and off-site facilities in a target area, and their ability to prevent pluvial inundation damage.

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