

Modeling of Stormwater Drainage/Overflow Processes Considering Ditches and their Related Structures

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(Received: Oct. 18, 2018 Accepted: Dec. 12, 2018)

Abstract

We propose a revised inundation flow model for urban areas in which storage effects of ditches are incorporated into stormwater drainage and overflow processes. Ditches are assumed to be on both sides of every street. Simulations were performed for two cases, i.e., considering and not considering ditches, and a significant difference was observed between the results for the two cases. However, the simulation results obtained by including the volume capacity of ditches in the volume of stormwater drainage boxes in the authors' conventional model are almost the same as the results obtained using our revised model. Consequently, while the volume of ditches has a significant effect on the inundation results, the stormwater drainage process can be simplified in the simulation model.

Keywords: pluvial inundation, ditch, stormwater drainage box, numerical simulation

1. INTRODUCTION

In recent years, pluvial inundation disasters have occurred frequently in urban areas worldwide. In Japan, such pluvial inundations are caused by short-time local torrential rainfall and long-term rainfall events. In certain cases, the high water level of external rivers makes it difficult to drain pluvial inundation water from residential areas. Consequently, pluvial inundation has led to high water depth and severe economic damage in a few cases. It has become more important to predict local risks of pluvial inundation with greater accuracy, which requires the improvement of simulation models.

One of the difficulties in simulating urban inundation is the complex system of drainage facilities. Several structures are involved in this system, such as storm drains, drainage boxes, ditches, connecting pipes, and sewer pipes. The scale of these structures is relatively smaller than that of overland structures, and detailed data of their locations and configurations are not available. Thus, in typical models, the drainage and overflow processes are simplified by omitting some of these structures.

For example, Takeda et al. (2007) assume that the inundation water on a ground surface is drained into sewer pipes through manholes with no covers and estimated drainage discharge is based on the weir equation. Chen et al. (2007) combine a 1D sewer model and a 2D overland

inundation model with grids containing manholes, and interaction discharge is calculated using the weir and orifice equations.

Our research group has developed and improved numerical models for urban pluvial inundation, considering the interaction process between overland surfaces and sewerage systems. In the first model (Kawaike et al., 2004), pump capacity is allocated to every computational mesh in its catchment area, which is equivalent to the maximum drainage discharge from the mesh. In the second model (Kawaike et al., 2010), storm drains are assumed along a sewer pipe with equal interval spacing and interaction discharge is calculated using the step-down and overflow equations. In the third model (Lee et al., 2013), storm drains are assumed at the center of every street mesh and interaction discharge is calculated using the weir and orifice equations. However, comparisons of the simulation results obtained using these models and actual measurement results show that simulated inundation areas are typically overestimated, particularly in the cases of small inundation events. This may be because stormwater is not drained before reaching the storm drain inlets in the simulation and computational meshes with even a small depth of stormwater are regarded as inundated areas.

In this study, our numerical model of urban inundation is revised in terms of the stormwater drainage or overflow processes between an overland surface and a sewerage system, and ditches and their related structures are incorporated into the model. Ditches are set on both sides of every street mesh, and stormwater on the overland surface is expected to drain into the ditches more easily.

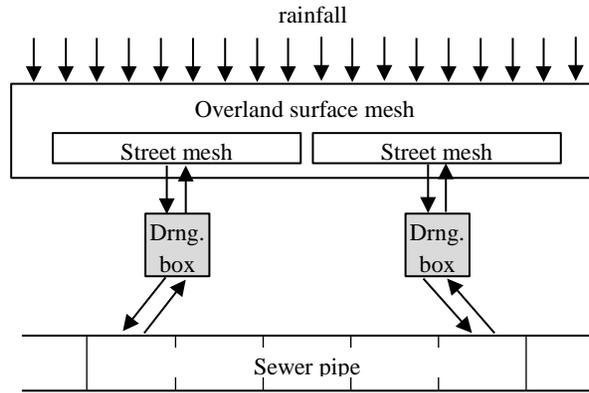
2. COMPUTATIONAL MODEL

We think that ditch capacity has a significant effect on the urban inundation process though it is usually neglected in numerical simulations. In this study, based on the conventional model for pluvial urban inundation, we improved the interaction part between 1D and 2D sub-models by incorporating ditches in the drainage/overflow process (revised model). Another method of improvement is incorporating ditch capacity into the drainage box capacity of the conventional model (simplified model). We compared the simulation results of these three models: the conventional model, the revised model, and the simplified model.

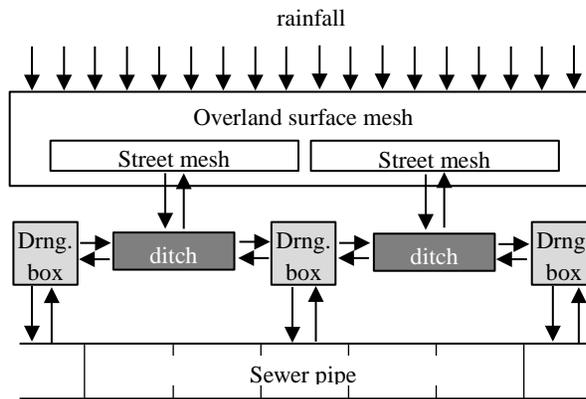
2.1 Model for pluvial inundation (Conventional model)

The numerical model for pluvial inundation that we developed (Lee et al., 2013; Lee et al., 2016) is an integration of a 2D model of overland inundation flow and a 1D model of sewer pipe flow. An overland surface is divided into triangular unstructured meshes to delineate the border between streets and buildings, and the meshes are categorized into streets, buildings, vacant spaces, etc.

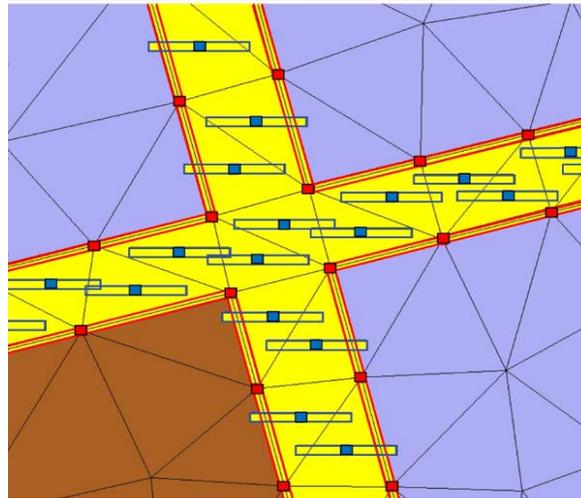
We assume that all street meshes possess a drainage box and calculate the interaction discharge between the drainage box and overland surface and between the drainage box and sewer pipe depending on their water levels or piezometric heads (**Fig. 1(a)**). The weir and orifice equations (equivalent to Eqs. (9), (11) and (10), (12), respectively, described later) are employed for this calculation. Such an integrated model and the coefficient values contained in the equations have already been validated through physical experiments (Lee et al., 2013).



(a) Stormwater drainage/overflow processes in the conventional model



(b) Stormwater drainage/overflow processes in the revised model



- Drainage box in the revised model
- == Ditch in the revised model
- ▬ Drainage box in the conventional model
- street
- building
- vacant area

(c) Location of drainage boxes and ditches in the conventional and revised models

Fig. 1 Schematic view of the conventional and revised models

In this model, while the length and the width of a drainage box are assumed as 20 m and 0.5 m, respectively, the height is determined by substituting the capacity of the connecting pipe (the diameter is assumed as 20 cm) between the drainage box and sewer pipe.

2.2 Revised model

In the above-mentioned numerical model for pluvial inundation, the stormwater drainage/overflow processes between the overland surface and sewer pipe are revised as shown in **Fig. 1(b)**. Ditches, which are typically located on the border between streets and residential blocks, are not necessarily prepared as a dataset of their coordinate positions, elevations, cross-sectional configurations, and potential discharge capacities as sewerage network data. In this study, we assume that ditches are located along the border between the street meshes and the meshes of other categories and drainage boxes are located at both ends of the ditches. We propose a new model (hereinafter ‘revised model’) considering the drainage/overflow processes through the ditches. The stormwater on a street mesh flows into a ditch, then to the drainage boxes at both ends of the ditch, and finally to the sewer pipe closest to the drainage boxes. If the piezometric head of the sewer pipe is higher than the surface elevation, the stormwater overflows on the overland surface in the opposite order to the above-mentioned drainage process: a sewer pipe, a drainage box, a ditch, and a street mesh. **Figure 1(c)** shows the locations of drainage boxes in the conventional model and the locations of ditches and drainage boxes in the revised model. The simulation results are sensitive to the width and height of ditches and drainage boxes, and these parameters are discussed in Section 3.2.

The interaction discharges of the respective processes are calculated as follows:

Interaction discharge between a street mesh and a ditch

We assume that ditches are located along the border line of street meshes. A ditch is not divided in the longitudinal direction, and its storage volume is only calculated using its length, width, and height in the simulation. The bottom elevation of the ditch is determined by subtracting its height from the surface elevation of the neighboring street mesh. In reality, a portion of the ditch is covered with lids, which regulate interaction discharge. However, the effects of lids are disregarded in this study for simplicity. This implies that the entire surface of the ditch is open.

- Drainage process ($h_s \leq h_r$)

$$Q_e = C_1 A_t \sqrt{2gh_r} : h_s/h_r \leq 2/3 \quad (1)$$

$$Q_e = C_2 A_d \sqrt{2g(h_r - h_s)} : h_s/h_r > 2/3 \quad (2)$$

- Overflow process ($h_s > h_r$)

$$Q_e = -C_1 A_t \sqrt{2gh_s} : h_r/h_s \leq 2/3 \quad (3)$$

$$Q_e = -C_2 A_d \sqrt{2g(h_s - h_r)} : h_r/h_s > 2/3 \quad (4)$$

where Q_e is the interaction discharge, H_r and H_d are the water levels of a street mesh and a ditch, respectively, z_r is the surface elevation of the street mesh, h_r and h_s are the overflow depth of the street mesh and the ditch, respectively ($h_r = H_r - z_r$, $h_s = H_d - z_r$, $h_r \geq 0$, $h_s \geq 0$), A_t is the attachment water area of the street mesh ($A_t = L_d \cdot h_r$), A_d is the smaller attachment water area

($A_d = L_d \cdot \min(h_r, h_s)$), L_d is the attachment length between the street mesh and ditch, and C_1 and C_2 are coefficients ($C_1 = 0.35$, $C_2 = 0.91$) validated by Lee (2013).

Interaction discharge between a ditch and a drainage box

- Drainage process ($h_s \leq h_d$)

$$Q_e = C_1 A_b \sqrt{2gh_d} \quad (5)$$

$$Q_e = C_2 A_b \sqrt{2g(h_d - h_s)} \quad (6)$$

- Overflow process ($h_s > h_d$)

$$Q_e = -C_1 A_b \sqrt{2gh_s} \quad (7)$$

$$Q_e = -C_2 A_b \sqrt{2g(h_s - h_d)} \quad (8)$$

where H_b is the water level of a drainage box, z_d is the bottom elevation of the ditch, h_d and h_s are the overflow depth of the ditch and the drainage box, respectively, ($h_d = H_d - z_d$, $h_s = H_b - z_d$, $h_d \geq 0$, $h_s \geq 0$) and A_b is the attachment water area between the ditch and drainage box.

Interaction discharge between a drainage box and a sewer pipe

- Drainage process ($h_p \leq h_b$)

$$Q_e = \frac{2}{3} C_{dw} L_p \sqrt{2g(h_b - h_p)^{3/2}} : (h_b - h_p) \leq B_0/2 \quad (9)$$

$$Q_e = C_{do} A_u \sqrt{2g(h_b - h_p)} : (h_b - h_p) > B_0/2 \quad (10)$$

- Overflow process ($h_p > h_b$)

$$Q_e = -\frac{2}{3} C_{dw} L_p \sqrt{2g(h_p - h_b)^{3/2}} : (h_p - h_b) \leq B_0/2 \quad (11)$$

$$Q_e = -C_{do} A_u \sqrt{2g(h_p - h_b)} : (h_p - h_b) > B_0/2 \quad (12)$$

where H_p is the piezometric head of a sewer pipe, z_b is the bottom elevation of a drainage box, h_b is the water depth of the drainage box ($h_b = H_b - z_b$), h_p is the piezometric height of the sewer pipe higher than z_b ($h_p = H_p - z_b$), L_p is the perimeter length of a connecting pipe, A_u is the cross-sectional area of the connecting pipe, B_0 is the diameter of the connecting pipe, and C_{dw} and C_{do} are the coefficients of the weir and the orifice equations, respectively ($C_{dw} = 0.48$, $C_{do} = 0.57$).

2.3 Simplified model

Instead of considering the detailed drainage/overflow processes in the revised model, we consider ditch capacity in a simpler manner. The effects of ditches are simply represented by incorporating the equivalent capacity of ditches into the capacity of drainage boxes in the conventional model (hereinafter ‘simplified model’). The simplified model proposed here is the same as the conventional model except for the increased capacity of the drainage boxes.

3. APPLICATION TO AN ACTUAL URBAN AREA

3.1 Target area

The target area of this study is the Mikazuki district, which is one of the sewer drainage areas in Kochi, Japan. This area is between Kuma River and Kosui River, and it experiences severe inundation damage caused by heavy rainfall. The Mikazuki district is shown in **Fig. 2**; its area is 1.94 km^2 . This target area is divided into 73,305 unstructured meshes, which are categorized into mountains, drainage channels, vacant spaces, buildings, and streets. The representative mesh size is approximately 10 m, and the representative divided length of the sewer pipes is approximately 3 m. The surface elevation and the five categories with different roughness of computational meshes are shown in **Figs. 3** and **4**, respectively. In this study, 77 sewer pipes and 78 manholes are considered, which are shown in **Fig. 5**. A pumping station with three pumps is located at the downstream end of this sewer pipe network. The outlet of the station faces Kosui River. The total capacity of the three pumps is $15.667 \text{ m}^3/\text{s}$.

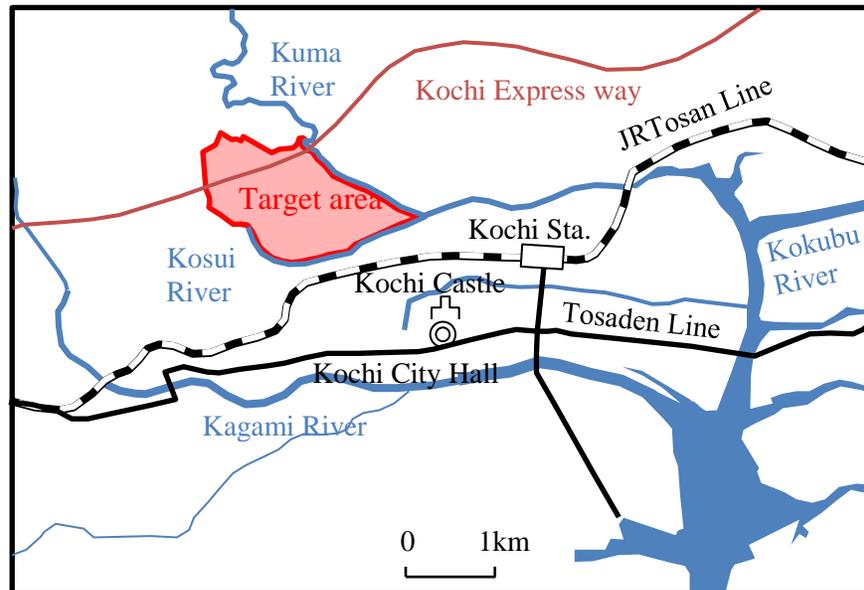


Fig. 2 Target area of the simulation

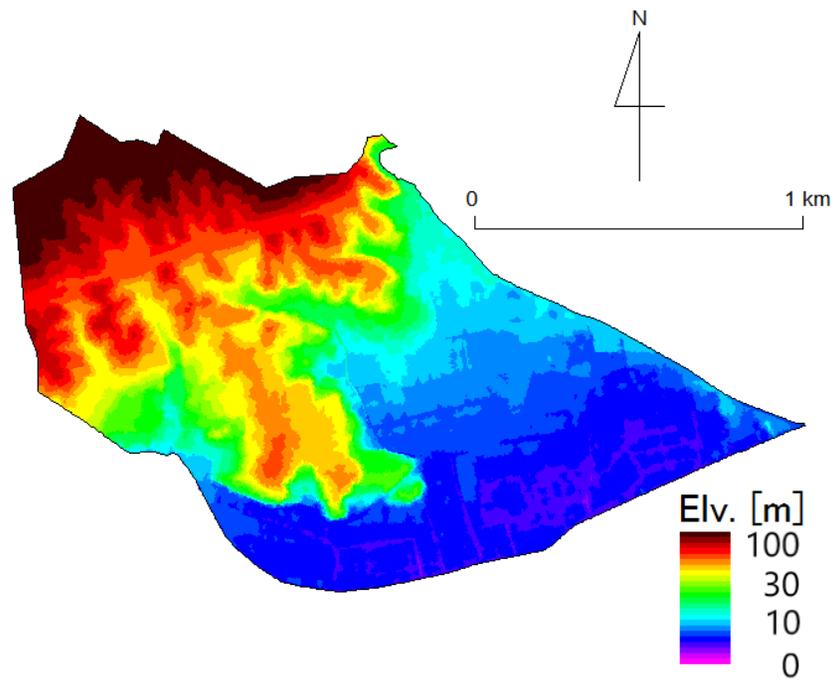


Fig. 3 Surface elevation of the target area

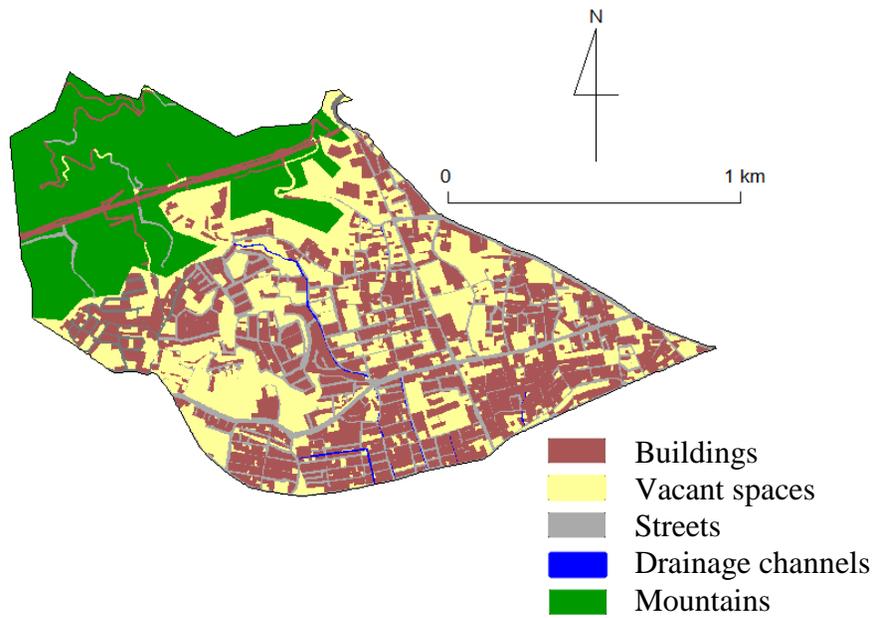


Fig. 4 Categories of the computational meshes

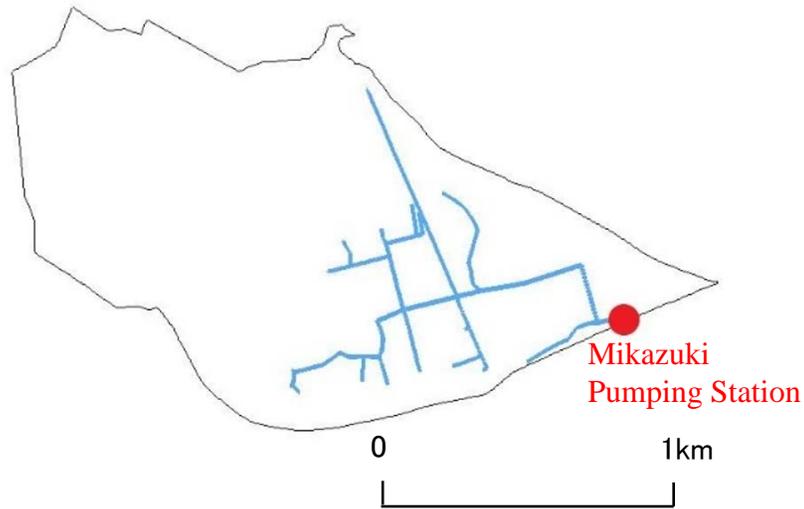


Fig. 5 Sewer pipes and the location of Mikazuki Pumping Station

This target area experienced inundation damage on August 3, 2014. The rainfall observed at the pumping station, the estimated overflow discharge from Kuma River and Kosui River, and the actual inundated area are shown in **Figs. 6, 7, and 8** (Kochi Prefecture, 2014), respectively. This inundation event is the target for simulation in this study. No inflow or outflow discharge in the target area is considered other than the above-mentioned observed rainfall, the estimated overflow discharge from Kuma River and Kosui River, and the drainage discharge from the pumping station. In the simulation, the effective rainfall is given to the surface of the target area, and the effective rainfall is derived from the observed rainfall multiplied by runoff ratio, 0.55 (Kochi Prefecture, 2014). The stormwater on the meshes other than street is not drained before it reaches any street meshes (conventional model) or ditches (revised model).

The computational duration is 48 hours, from 00:00 August 2 to 00:00 August 4.

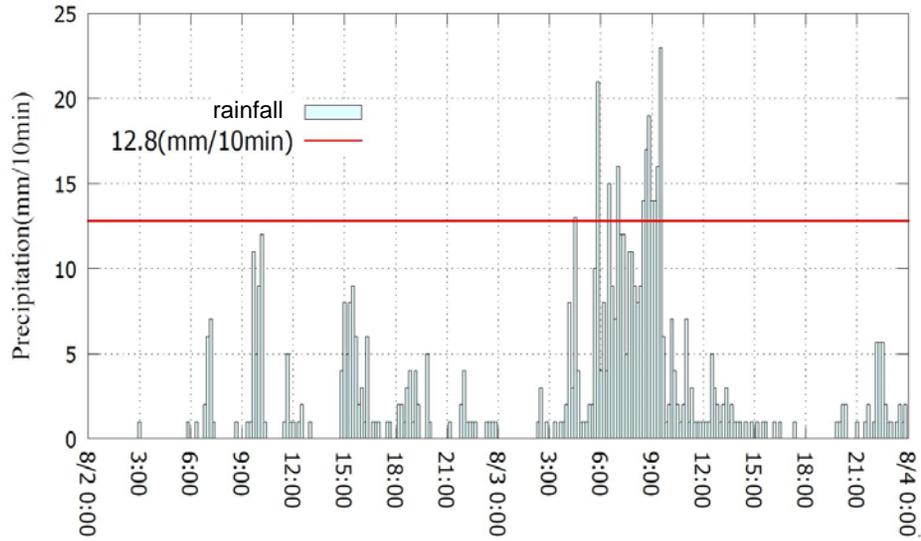


Fig. 6 Hyetograph from 2 to 3 August, 2014 (Kochi Pref., 2014)
 (The red line in the figure denotes the designated rainfall intensity of the sewerage system in Kochi city, which is 77 mm/hr = 12.8 mm/10 min.)

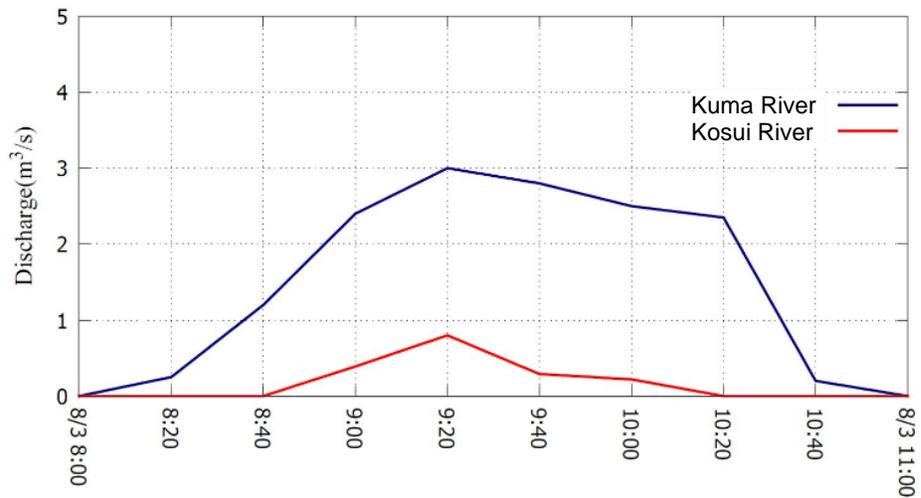


Fig. 7 Estimated overflow discharge from Kuma River and Kosui River on 3 August, 2014
 (Kochi Pref., 2014)

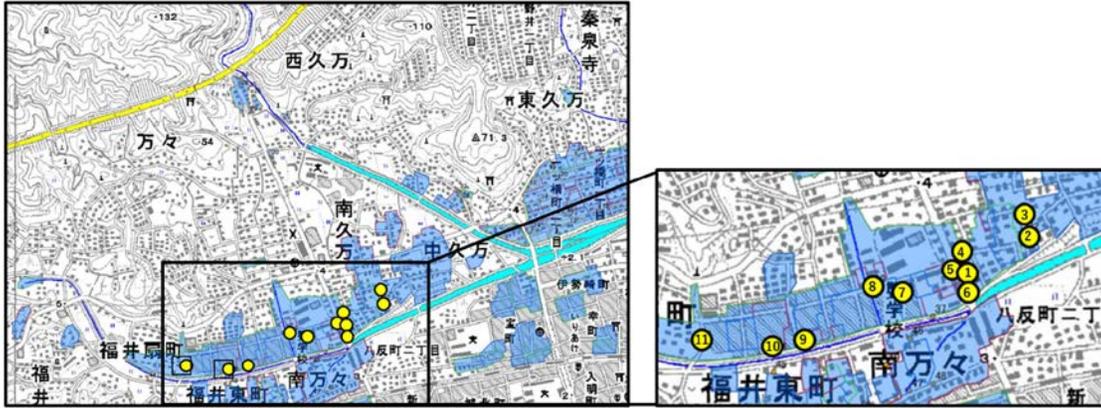


Fig. 8 Actual inundation area and the measurement points of inundation water depth (Kochi Pref., 2014)

3.2 Configuration of ditches and drainage boxes

It is necessary to determine the configurations (length, width, and height) of ditches and drainage boxes for the simulation. However, the positions of ditches and drainage boxes are hypothetical. Even if the precise positions could be reflected in the simulation, it would be difficult to assign individual configurations to ditches and drainage boxes. We assume a uniform configuration for all ditches and drainage boxes installed in the target area. We consider seven configuration cases, as shown in **Table 1**.

Table 1 Configuration of ditches and drainage boxes (unit: m)

	Ditch		Drainage box		
	width	height	width	length	height
Case 1	0.4	0.4	0.5	0.5	0.7
Case 2	0.5	0.5	0.5	0.6	0.8
Case 3	0.6	0.6	0.5	0.7	0.9
Case 4	0.7	0.7	0.5	0.8	1.0
Case 5	0.8	0.8	0.5	0.9	1.1
Case 6	0.9	0.9	0.5	1.0	1.2
Case 7	1.0	1.0	0.5	1.1	1.3

The maximum inundation depths at 11 points (indicated in **Fig. 8**) obtained through the simulation are compared with the measured depth. The measured depth, computed depth, and the averaged difference between them at 11 points are shown in **Table 2**. The minimum difference appears in Case 6, and the computed depths are close to the measured values in Cases 4, 5, and 7. Hereinafter, the configuration of Case 4 is regarded as the basic configuration because the inundated area is the closest to the actual area in Cases 4 and 5 and because the uniform cross-section of 0.9 m × 0.9 m in Case 6 appears to be considerably larger than the actual section size.

Table 2 Comparison between the measured depth and calculated maximum depth
(unit: m)

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	Averaged difference from the measured depth
Measured depth	0.40	0.80	0.55	0.70	0.38	0.28	0.50	0.65	0.60	0.45	1.12	—
Case 1	0.690	0.928	0.667	0.662	0.661	0.288	0.551	0.647	0.918	0.458	1.199	0.120
Case 2	0.672	0.908	0.647	0.644	0.644	0.272	0.537	0.636	0.910	0.450	1.192	0.113
Case 3	0.661	0.894	0.633	0.633	0.633	0.260	0.528	0.629	0.906	0.446	1.188	0.110
Case 4	0.633	0.862	0.601	0.605	0.605	0.232	0.509	0.616	0.897	0.437	1.180	0.102
Case 5	0.625	0.853	0.593	0.597	0.597	0.224	0.499	0.606	0.893	0.434	1.178	0.101
Case 6	0.598	0.820	0.561	0.570	0.570	0.196	0.477	0.588	0.886	0.427	1.172	0.098
Case 7	0.569	0.783	0.524	0.541	0.542	0.168	0.458	0.572	0.879	0.420	1.167	0.102

Table 3 Maximum depth calculated using the revised and conventional models
(unit: m)

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
Measured depth	0.40	0.80	0.55	0.70	0.38	0.28	0.50	0.65	0.60	0.45	1.12
Revised model (Case 4)	0.633	0.862	0.601	0.605	0.605	0.232	0.509	0.616	0.897	0.437	1.180
Conv. model No ditch volume	0.678	0.919	0.659	0.648	0.649	0.276	0.537	0.630	0.902	0.444	1.188
Simplified model with ditch volume	0.617	0.853	0.594	0.587	0.589	0.216	0.492	0.596	0.877	0.418	1.164

3.3 Comparison between the conventional model and revised model

As mentioned in the previous section, the configuration of Case 4 is applied to ditches and drainage boxes in the simulation of the revised model. In the simulation of the ‘conventional model’ in this section, the configuration of Case 4 is adopted for drainage boxes and the capacity of the connecting pipes between sewer pipes and drainage boxes is neglected though it was included in the drainage box capacity in the original ‘conventional model’ (Lee et al., 2016).

The maximum water depths at 11 points for both models are shown in **Table 3**. The temporal changes in the water volumes of the overland surface, sewer pipes, ditches, and drainage boxes for the models are shown in **Fig. 9**. The inundation water volume at the peak time differs significantly between the two models. The water volume on the overland surface in the revised model considering the processes of ditches is considerably smaller than that in the conventional model. The drainage box capacity in the conventional model is sufficiently small. However, in the revised model, the capacities of ditches and drainage boxes, which store a water volume equivalent to one quarter that of the overland inundation water, have significant effects on the inundation water volume on the overland surface.

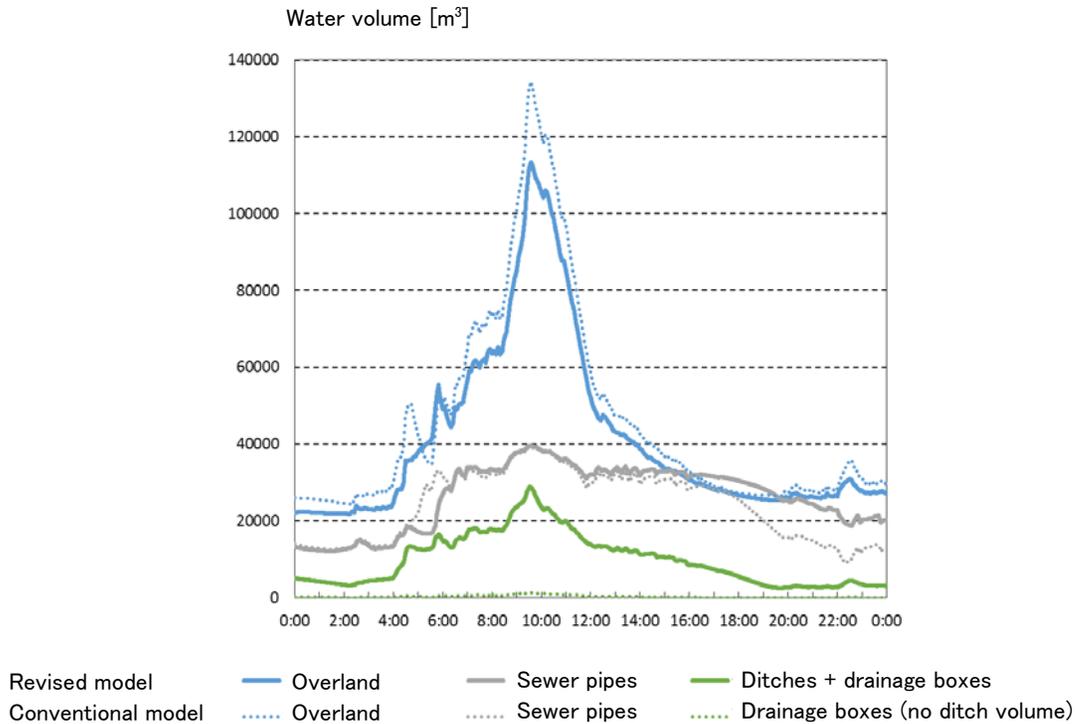


Fig. 9 Comparison between the revised and conventional models without ditch volume (Water volume of the overland surfaces, sewer pipes, ditches and drainage boxes)

The water volumes of sewer pipes in the two models are almost the same before 16:00. On the contrary, the water volume of overland inundation is always larger in the conventional model. This implies that inundation water is stored or drained in ditches in the revised model. After 16:00, the difference between the overland inundation water volume for the models decreases while the difference between the water volume of sewer pipes for the models increases. This

implies that overland inundation water stagnates at ditches or drainage boxes and it takes longer to reach sewer pipes.

3.4 Comparison between the revised model and simplified model

In the simulation of the simplified model, the height and length of drainage boxes are fixed as 0.3 m and 5.0 m, respectively, and the width is calculated as 1.83 m from the total capacity of the ditches and the drainage boxes of Case 4.

The maximum water depths at 11 points for both models are shown in **Table 3**. The temporal changes in the water volumes of the overland surface, sewer pipes, ditches, and drainage boxes for the models are shown in **Fig. 10**. The overland inundation water volume around the peak time is almost the same for both models, while it is larger in the simplified model before and after the peak time. This implies that the maximum inundation depth obtained through the simulation of the simplified and revised models is almost the same at several points. However, the simulation results of the detailed inundation/drainage processes at depths other than the peak depth are different between the two models. That difference might be caused by the location and the surface area of storm drains in both models, which could be regarded as the effects of lids over the ditches. This requires further investigation.

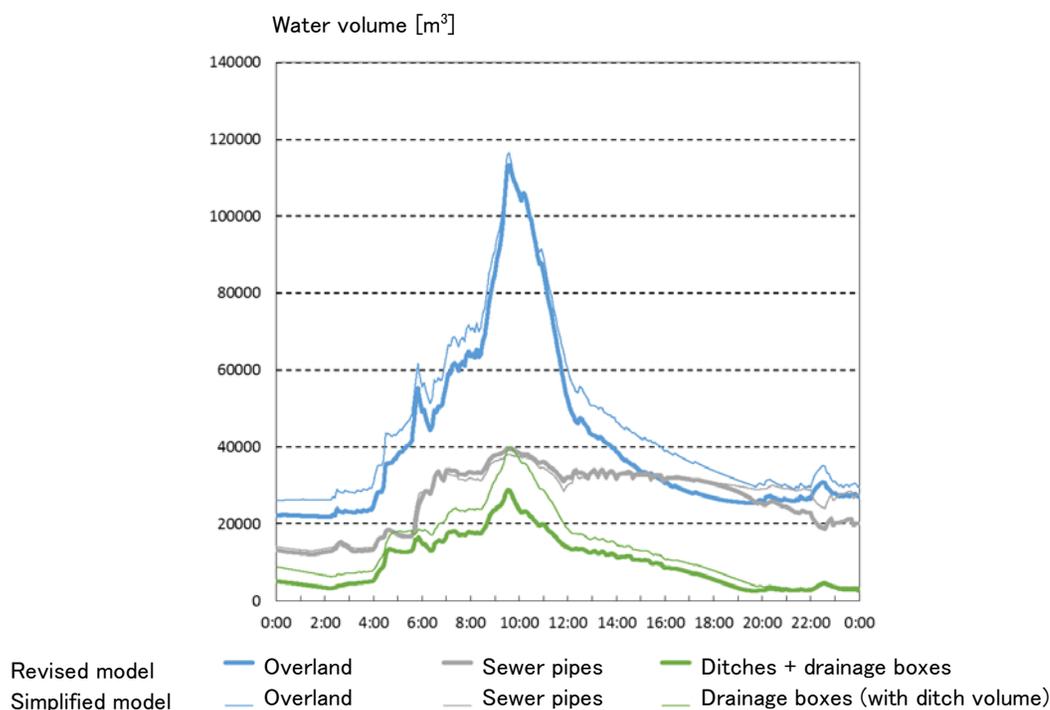


Fig. 10 Comparison between the revised and simplified models with ditch volume (Water volume of the overland surfaces, sewer pipes, ditches and drainage boxes)

4. CONCLUSIONS

In this study, we revised an inundation flow model with the effects of ditches in the stormwater drainage/overflow processes. The conclusions obtained from the study are summarized below.

- Assuming that ditches exist on every border between the street mesh and other meshes, the effect of ditch capacity on the inundation water volume on the overland surface cannot be neglected.
- The conventional model without ditch capacity overestimates the peak volume of the inundation water on the overland surface.
- The conventional model can represent almost the same inundation situation at the peak time as the revised model simply by considering the ditch effects by incorporating ditch capacity into the capacity of drainage boxes.

In conclusion, ditch capacity has significant effects on overland inundation, and the simplified model, incorporating the ditch capacity into the capacity of drainage boxes, is sufficient if the purpose is to assess the inundation depth at the peak time.

Acknowledgement

This work was supported by JSPS KAKENHI Grant-in-Aid for Young Scientists (A) 16H06100 and a grant (17CTAP-C095650-03) from the Infrastructure and Transportation Technology Promotion Program funded by the Ministry of Land, Infrastructure and Transport of the Korean government.

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