# NUMERICAL SIMULATION OF FLOOD MITIGATION EFFECTS OF AN ASSUMED RETARDING BASIN

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## ABSTRACT

Recently, there have been several flood disasters in Japan caused by heavy rainfall. To mitigate the damage caused by such disasters, various structural and non-structural measures have been adopted. However, it is still difficult to reduce the damage. A huge scale of tentative water storage functions such as a retarding basin could be considered. We evaluated the mitigation effect of an assumed retarding basin against the actual flood event of 2013 in Kyoto, Japan, by conducting numerical simulations. During this flood event, the maximum water level exceeded the designed high water level at a few points. For the best combination of the length and height of the overflowing weir, and assuming a surrounding wall of this retarding basin, 37 million $m^3$ of flood water was stored. Consequently, the peak flood water level was decreased by 0.8 m, and the water level did not exceed the designed high water level at any point. Thus, a retarding basin has mitigation effects on the exceedance flood hazards to some extent. Further, the total population of Japan is decreasing. If land use, particularly residential areas, can be efficiently regulated to the safer places, this type of retarding basin can be one of the most effective and feasible countermeasures.

*Keywords*: Flood disaster, retarding basin, numerical simulation, Ogura Pond, overflow

## 1. INTRODUCTION

In 2013, the western part of Japan was hit by a severe typhoon, and the flood water level of the Yodo River increased due to heavy rainfall. The observed peak water level exceeded the designed high water level at several observatories of the Yodo River basin. Although a few dams in the upstream region stored the flood water to almost full capacity of their reservoirs and controlled the outflowing discharge, the overtopping flow occurred in the downstream region. Thus, extreme heavy rainfall events and subsequent fluvial inundation disasters tend to increase in recent years due to climate change.

To prevent or mitigate these inundation disasters, river embankments have been constructed and reinforced on both sides of the rivers. Flood control dams have also been constructed to decrease the outflowing discharge in the downstream regions. However, the mitigation effects of these flood control facilities are limited during excessive flood hazards. Therefore, we need to consider different structural and non-structural countermeasures against flood disasters than conventional methods. A huge scale of tentative water storage functions such as a retarding basin might well be worth consideration as an additional countermeasure.

In this study, we assume a retarding basin along the Yodo River and evaluate its flood mitigation effects by conducting numerical simulations. There exist several problems with the implementation of a retarding basin in the real field, such as difficulties in obtaining a large area to store flood water, a huge amount of compensation cost for the usage of agricultural fields, and limited effects on flood events that exceed the storage capacity of the basin. However, we will not discuss these feasibilities of the retarding basin. Instead, based on the future possibility, hydraulic functions and mitigation effects are evaluated here.

## 2. STUDY AREA

The Yodo River is one of the largest rivers in the western Japan. Its origin is the Lake Biwa, the largest lake in Japan. There are more than one hundred tributaries of the Lake Biwa, and only one outflowing river, the Seta River that changes its name to the Uji River in the downstream region. The Uji River merges with the Katsura
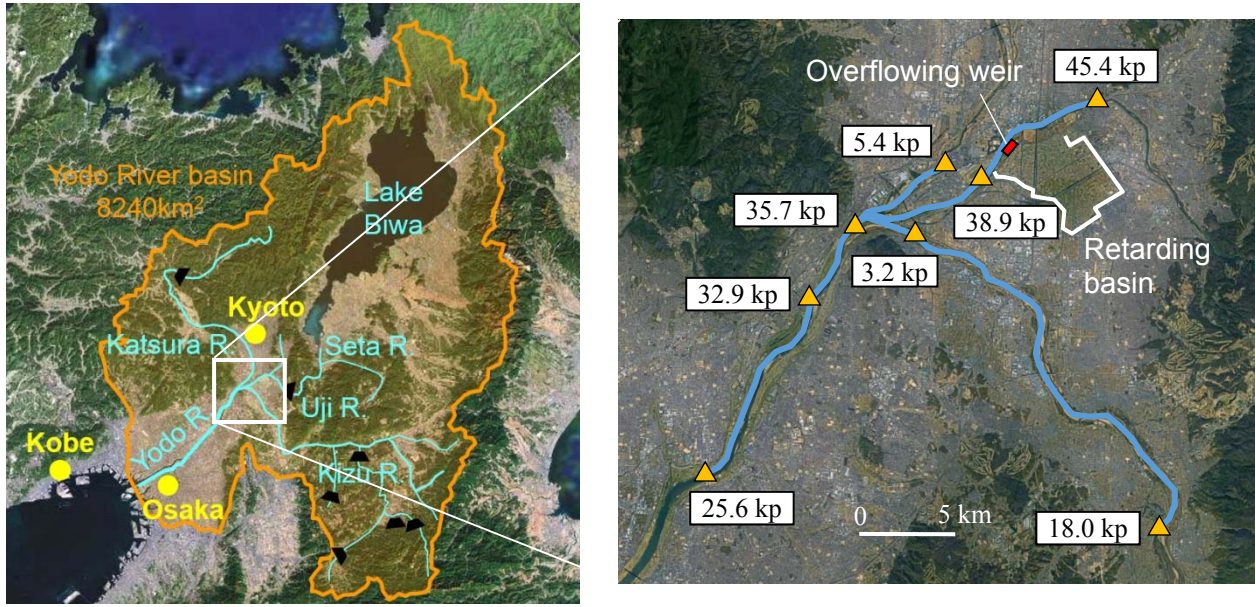
Figure 1. Yodo River system and the location of the study area and the assumed retarding basin.

River and the Kizu River at one point, and this convergence of three rivers is called the Yodo River that flows into the Bay of Osaka. Figure 1 shows the Yodo River basin area and the locations of the above-mentioned rivers. The population of the river basin is more than 10 million, including large cities such as Osaka and Kyoto. Therefore, a fluvial inundation disaster can cause a huge amount of damage in this river basin.

The river evaluated in this study is the Uji River that flows through the southern part of Kyoto City, and a retarding basin is assumed neighboring the Uji River. In the assumed retarding basin, there used to be a large pond, the Ogura Pond, which was completely reclaimed in 1941 for the deterioration of its water quality. Currently, the elevation of this area is lower than the surrounding area, and most of this land is used as paddy fields.

## 3. SIMULATION MODEL

The model employed in this study is a one-dimensional unsteady flow model. The governing equations are as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

$$\frac{1}{g}\frac{\partial v_r}{\partial t} + \frac{v_r}{g}\frac{\partial v_r}{\partial x} + \frac{\partial h_r}{\partial x} = s_0 - s_f \tag{2}$$

, where $A$ is the wetted cross section area, $Q$ is the flow discharge, $q$ is the lateral inflow discharge per unit length, $v_r$ is the flow velocity, $h_r$ is the water depth, $s_0$ is the bed slope, and $s_f$ is the friction slope. The above equations are solved using the characteristics method in which the water levels and flow discharges are calculated at every cross section along the rivers (Inoue et al., 2000).

When the water level exceeds the height of the embankment, the overflowing discharge is calculated. The following weir formulas are used:

$$Q_{of} = sgn \cdot 0.35 h_1 L\sqrt{2gh_1} \quad \text{if } h_2/h_1 \leq 2/3 \tag{3}$$

$$Q_{of} = sgn \cdot 0.91 h_2 L\sqrt{2g(h_1 - h_2)} \quad \text{if } h_2/h_1 > 2/3 \tag{4}$$

, where

$$h_1 = H_1 - Z_w, \tag{5}$$

$$h_2 = H_2 - Z_w, \tag{6}$$
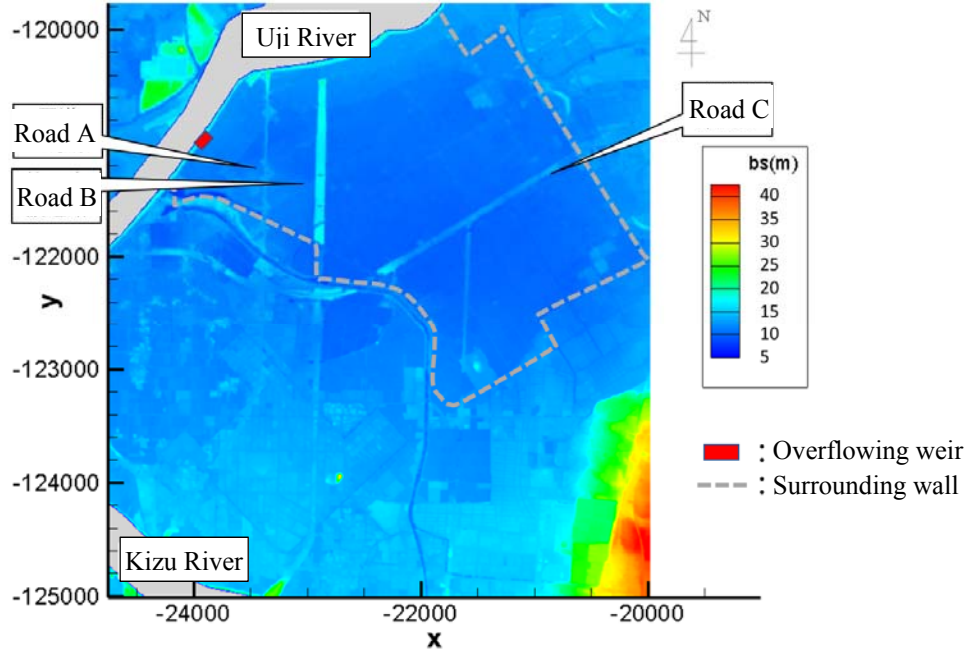
$$sgn = \frac{|H_r - H_b|}{H_r - H_b} \tag{7}$$

Figure 2. Surface elevation around the assumed retarding basin.

$Q_{of}$ is the overflowing discharge (positive value means the direction is from the river towards the retarding basin), $H_1$ and $H_2$ are the higher and lower water levels between the river side and retarding basin side, respectively, $L$ is the length of the overflowing weir, $Z_w$ is the elevation of the overflowing weir, $H_r$ and $H_b$ are the water levels of the river side and retarding basin side, respectively. The lateral inflow discharge per unit length, $q$, in Eq. (1) is calculated by dividing $Q_{of}$ by the interval length between computational river sections.

The overflowed water is two-dimensionally inundated and stored in the retarding basin. The horizontal flow of the inundation water is calculated using the two-dimensional shallow water equations as follows:

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = 0 \tag{8}$$

$$\frac{\partial(uh)}{\partial t} + \frac{\partial(u^2h)}{\partial x} + \frac{\partial(uvh)}{\partial y} = -gh\frac{\partial(z_b + h)}{\partial x} - \frac{gn^2u\sqrt{u^2 + v^2}}{h^{1/3}} \tag{9}$$

$$\frac{\partial(vh)}{\partial t} + \frac{\partial(uvh)}{\partial x} + \frac{\partial(v^2h)}{\partial y} = -gh\frac{\partial(z_b + h)}{\partial y} - \frac{gn^2v\sqrt{u^2 + v^2}}{h^{1/3}} \tag{10}$$

, where $h$ is the flow depth, $u$ and $v$ are $x$- and $y$-directional flow velocities, respectively, $z_b$ is the bed elevation, and $n$ is the Manning's roughness coefficient. The finite difference method and rectangular computational meshes are used to solve the above governing equations (Iwasa and Inoue, 1982).

## 4. APPLICATION OF PROPOSED MODEL TO STUDY AREA

### 4.1 Study area condition

The proposed model is applied to the study area. The study reach of the river is indicated in Figure 1, i.e., the Yodo River and the Uji River (from 25.6 kp to 45.4 kp), the Katsura River (from the confluence to 5.4 kp), and the Kizu River (from the confluence to 18.0 kp). Along these rivers, 221 computational cross sections are established at the interval of 200 m.

In this area, an assumed retarding basin is set as shown in Figure 1, which is delineated by a surrounding wall and connected to the Uji River through an overflowing weir. This retarding basin is divided into rectangular computational meshes. The number of meshes is 477 and 364 in $x$- and $y$- directions, respectively, and the mesh size is approximately 10 m. The area of the delineated retarding basin is 6,784,814 m². The assumed overflowing weir is established at the location of 41.6 kp. The height and length of the overflowing weir are described in the following section. There are a few elevated roads constructed in the study area as shown in Figure 2, and box culverts that enable the inundation water to pass through below the roads are considered in the simulations.

### 4.2 Input conditions of flood event

In this study, the actual flood event of 2013 is selected as an extreme input condition. During this flood event, the observed peak water level exceeded the designed high water level at three observatories (45.4 kp and 38.9 kp of the Uji River, and 5.4 kp of the Katsura River) in the study reach. The estimated flow discharge at the up-
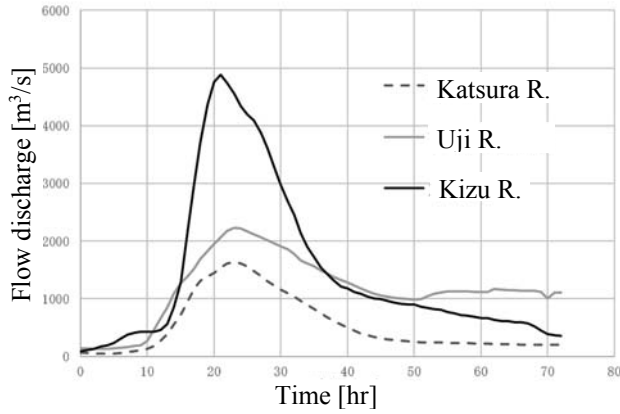
Figure 3. Flow discharge at the upstream end of the Katsura, Uji, and Kizu River.
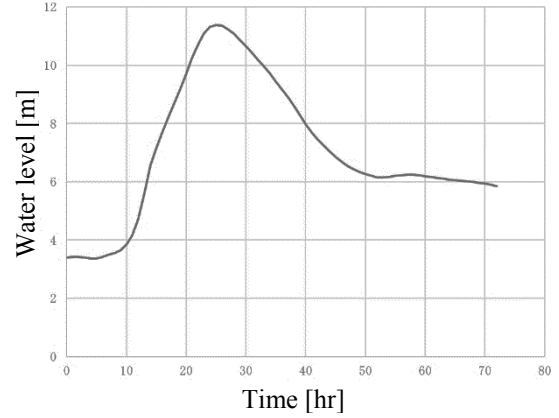


Figure 4. Water level at the downstream end of the Yodo River.

Table 1. Comparison between the observed and calculated peak water levels.

| River section | Observed level [m] | Calculated level [m] | Error [m] |
|---|---|---|---|
| 45.4 kp of Uji River | 17.4 | 17.4 | -0.076 |
| 18.0 kp of Kizu River | 28.4 | 28.4 | -0.018 |
| 5.4 kp of Katsura River | 17.5 | 17.4 | -0.089 |
| 35.7 kp of Yodo River | 16.0 | 16.0 | 0.054 |

Table 2. Computational cases and simulation results.

| | Weir configuration | | Simulation results | | | |
|---|---|---|---|---|---|---|
| | Weir length [m] | Weir height [m] | Surrounding wall | | Maximum mitigation height of water level [m] | Stored water volume [$\times 10^3$ m$^3$] |
| | | | Required elevation [m] | Maximum height [m] | | |
| Case 1 | 100 | 13.0 | 15.3 | 6.2 | 0.61 | 28,887 |
| Case 2 | 100 | 14.0 | 14.5 | 5.3 | 0.47 | 23,538 |
| Case 3 | 100 | 15.0 | 12.4 | 3.2 | 0.25 | 9,937 |
| Case 4 | 100 | 16.0 | 10.4 | 1.3 | 0.08 | 2,009 |
| Case 5 | 150 | 13.0 | 16.5 | 7.4 | 0.80 | 36,880 |
| Case 6 | 150 | 14.0 | 15.2 | 6.1 | 0.63 | 28,393 |
| Case 7 | 150 | 15.0 | 13.0 | 3.8 | 0.34 | 13,609 |
| Case 8 | 150 | 16.0 | 10.6 | 1.5 | 0.11 | 2,820 |

stream end of three rivers (45.4 kp of the Uji River, 5.4 kp of the Katsura River, and 18.0 kp of the Kizu River) is shown in Figure 3. The observed water level at the downstream end of the Yodo River (25.6 kp) is shown in Figure 4.

To determine the roughness coefficient of the river sections, flood simulation using the above-mentioned input conditions is conducted without considering the retarding basin, and the calculated flood water levels are compared with the observed ones, as summarized in Table 1. The table indicates that good agreement is obtained between the simulated water levels and the observed ones based on the determined roughness coefficient.

## 5. RESULTS AND DISCUSSIONS

### 5.1 Simulation cases

In the numerical simulations, two lengths (100 m and 150 m) and four heights (13.0 m, 14.0 m, 15.0 m, and 16.0 m) are selected for the overflowing weir configuration. Combining all the lengths and heights of the overflowing weir, a total of eight cases of simulations are conducted.
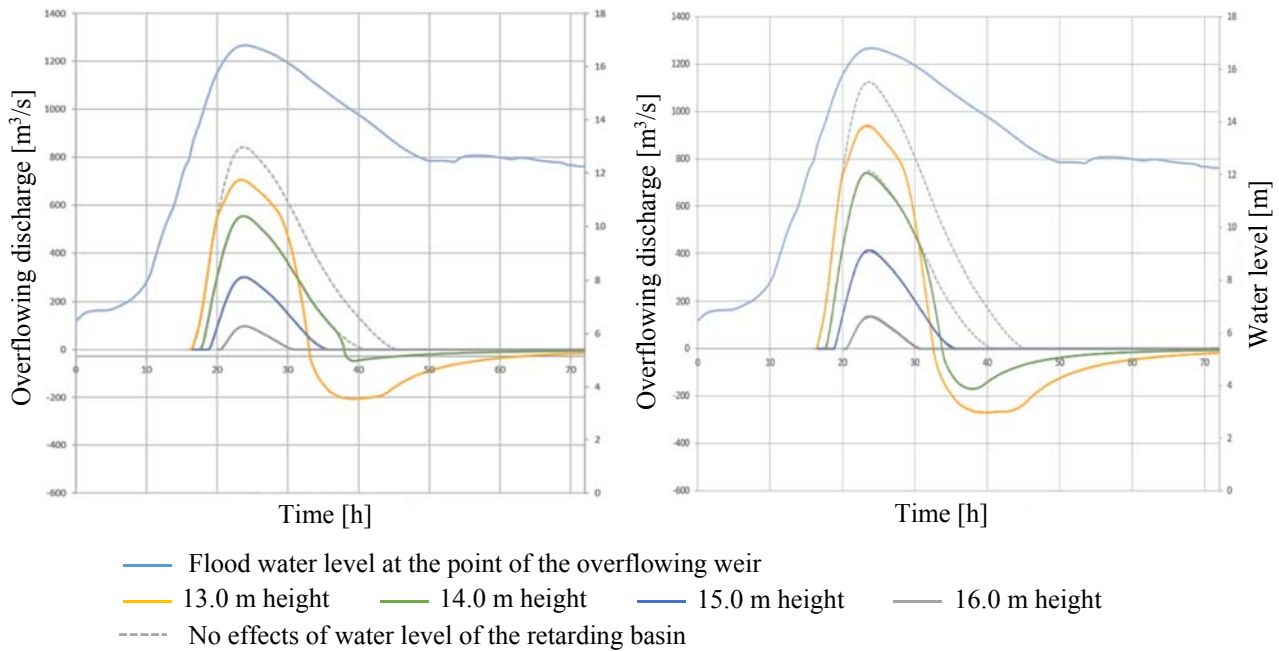
Figure 5. Overflowing discharge; the positive direction is from the river to the retarding basin.
(Left: 100 m weir length, Right: 150 m weir length)

## 5.2 Overall simulation results

The simulation results are summarized in Table 2. In the table, the required elevation of the surrounding wall implies the calculated water level, assuming that the water is stored horizontally in the retarding basin, and the maximum height is calculated from the lowest surface elevation to the required elevation. The maximum mitigation height of water level implies the maximum difference in the simulated peak water level for the case that do not consider the retarding basin among all river sections. The stored water volume implies the maximum water volume stored in the retarding basin during calculations. Consequently, the peak water level can be significantly decreased by 0.80 m in Case 5 (150 m length and 13.0 m height) by storing 37 million m$^3$ of flood water in the retarding basin.

Figure 5 shows the overflowing discharge of each case. The negative value implies the overflowing discharge from the retarding basin to the river. The figure also indicates the overflowing discharge calculated using only the one-dimensional model and the weir formulas [Eqs. (1)-(7)], where the effects of the stored water level in the retarding basin are not considered. In Figure 5, a much more significant difference in overflowing discharge can be found among different weir heights than different weir lengths, implying that overflowing discharge is more sensitive to weir height than weir length. The simulation results also indicate that the stored water level in the retarding basin has significant effects on the overflowing discharge.

## 5.3 Configuration of retarding basin

### 5.3.1 Flood water level mitigation effects

Figure 6 shows the peak water level calculated in Cases 5, 6, 7, and 8 (150 m weir length) along the Yodo River and the Uji River. In Cases 5 (150 m length and 13.0 m height) and 6 (150 m length and 14.0 m height), indicated using yellow and green lines in Figure 6, respectively, the peak water level does not exceed the designed high water level at any river section. Consequently, this retarding basin can be expected to mitigate the flood disaster significantly by reducing the peak water level.

### 5.3.2 Height of surrounding wall

In the simulations, the height of the surrounding wall was set as sufficiently high elevation to prevent the stored water from spilling out of the retarding basin. In Case 5, the maximum wall height was calculated as 7.4 m, where the mound of road C was actually constructed to be 5-7 m high. The maximum wall height around the residential area was 5.5 m, which can be regarded as the feasible height of the wall.

Figure 7 shows the changes in the inundated water depth of the retarding basin of Case 1 with time. In this retarding basin, water is firstly stored in the western side of the basin, and the water depth of the eastern side is increases gradually. In the western side, there exists a water level difference of 0.6 m between the highest water level at the beginning time and the horizontally stored water level. Consequently, this height of 0.6 m should be considered as the additional height of the surrounding wall to achieve the required elevation. In this study, the
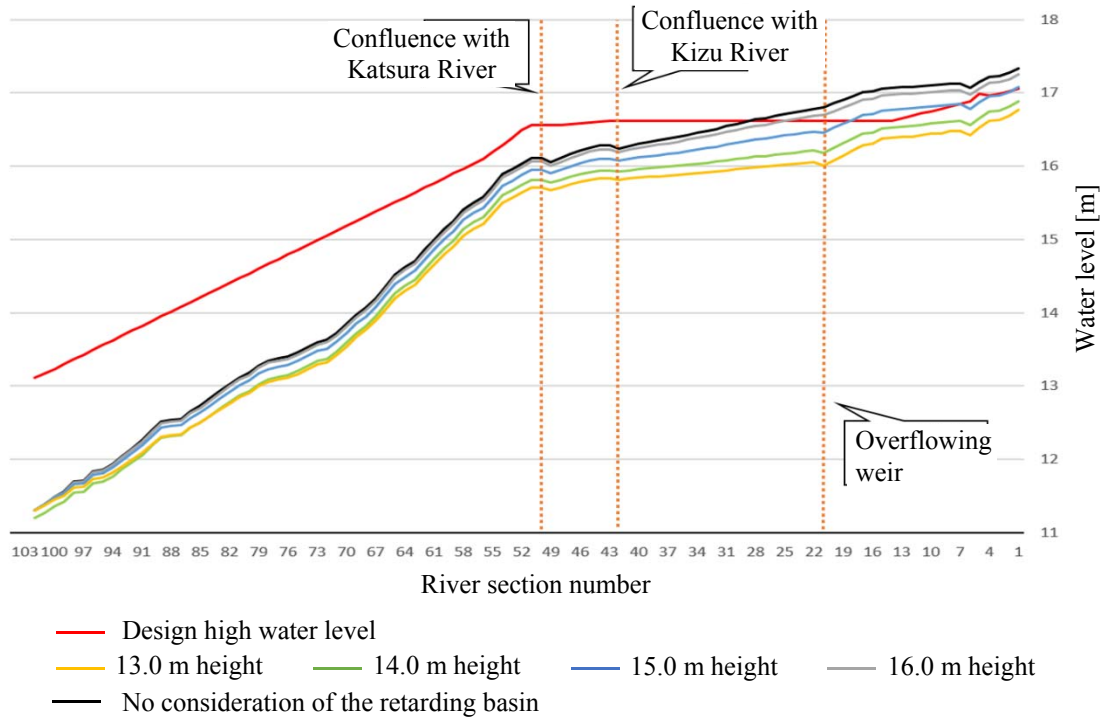
Figure 6. Peak water level along the Yodo River and the Uji River in cases with weir length of 150 m.
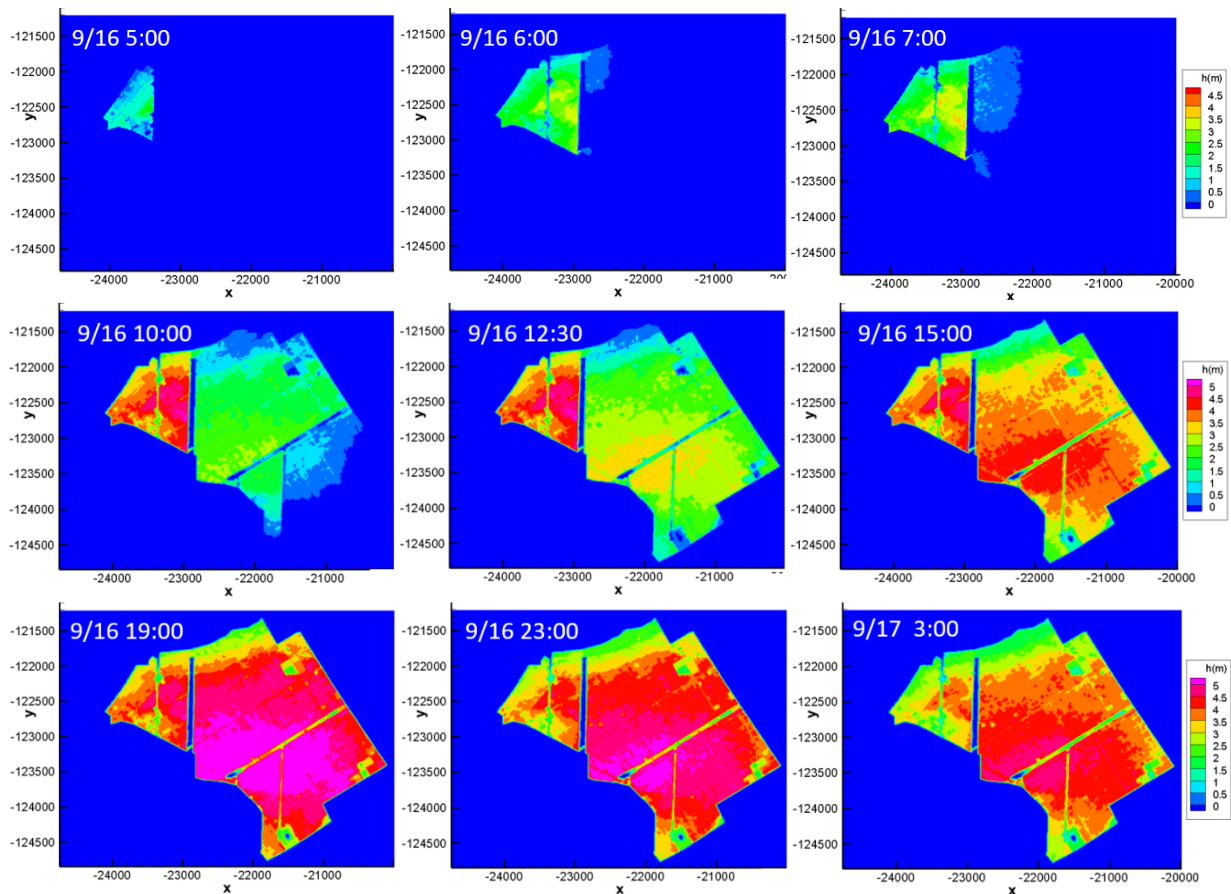


Figure 7. Changes in inundated water depth of Case 1 (100 m length and 13.0 m height) with time.

surrounding wall height with additional height of 0.6 m does not exceed the height of the river embankment at the location of the assumed overflowing weir in any case.

### 5.3.3 Height of overflowing weir

Particularly in cases of low elevation of the overflowing weir, there is a possibility that the retarding basin is not able to decrease the peak flood water level efficiently as expected due to the full storage of water at the early

stage of a flood event. Although full storage was also found in some cases in this study, the time of the peak overflow discharge was almost the same in all cases, and significant effects on peak water level were observed in cases of low elevation of the overflowing weir (e.g. Cases 1, 5, and 6). In this scale of flood events, low elevation of the overflowing weir would be effective to mitigate the peak water level, but the inundation frequency of the retarding basin is another problem that needs to be discussed in terms of the damage to farmland and compensation cost.

## 6.   CONCLUSIONS

In this study, the mitigation effects of an assumed retarding basin are evaluated by conducting numerical simulations. Using the actual flood event of 2013 as an extreme input condition, the following conclusions were obtained.

1. In case of the overflowing weir with length of 150 m and height of 13.0 m, the peak water level could be decreased by 0.8 m by storing 37 million m$^3$ of flood water in the retarding basin, which decreased the flood water level than the designed water level at all river sections. Therefore, it can be concluded that significant mitigation effects of a retarding basin can be expected using an appropriate configuration of the overflowing weir.

2. The mitigation effects of a retarding basin are significantly affected by the length and height of the overflowing weir. To determine the configuration, it is necessary to consider the scale of the designed flood event, frequency of using the basin, and topographical condition of the basin area.

In addition, the following points should be improved and discussed in the future.

1. In this simulation, the boundary condition of the downstream end was the observed water level at 25.6 kp. However, if a retarding basin works efficiently, its water level should also change. To evaluate more in detail, the study reach of the Yodo River should be extended to the river mouth.

2. The feasibility of the retarding basin was not discussed in this study. In the future, the total population of workers in the agricultural industry is predicted to continue to decrease in Japan. The flood mitigation strategies in the whole river basin should be discussed, including the possibility of a retarding basin, future population, and efficient land-use regulations to live in safer places.

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