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# OPTIMIZED RESERVOIR OPERATION FOR FLOOD CONTROL UNDER EXTREME EVENTS BASED ON RAINFALL-RUNOFF-INUNDATION ANAYLSIS IN THE UPPER KATSURA RIVER BASIN, JAPAN

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## ABSTRACT

In order to develop a science-based method to design the optimal flood control operation of reservoirs during extreme flood events that may increase under the changing climate, a method is proposed for optimization of reservoir's flood control operation based on inundation analysis in the downstream. At first, rainfall scenarios are developed for extreme flood events. Multiple patterns of rainfall scenarios with different scale and spatio-temporal distribution are considered to take different patterns of runoff into account. River discharge, inundation area and depth in the target river basin are then estimated for the rainfall scenarios using the RRI model, a rainfall-runoff-inundation model. Optimal reservoir operation for flood control is analyzed from results of the inundation analysis of the considered extreme flood scenarios. The proposed method was applied to the Hiyoshi Reservoir in the Upper Katsura River in Japan, and optimal flood control strategy of the reservoir was respectively identified for each scenario of extreme flood event.

**Keywords:** Reservoir operation, flood control, rainfall-runoff-inundation analysis, extreme event, flood damage

## 1 INTRODUCTION

Flood management is one of the most important issues for development of our society enhancing security and safety of the people. Constructing reservoirs in the upstream is an effective option to raise the flood protection level in the target river basin, because all the river section in its downstream can be protected by a reservoir once it is constructed and sets in operation. Storage capacities for flood control of those reservoirs are usually designed in accordance with a target level of flood protection designated by a river development and management plan, in conjunction with river development works with other type of flood management measures such as construction of levees or enlargement of river cross sections. Operation policies of those reservoirs for flood control are also designed in a same fashion in most cases, so that they can work most effectively to prevent or mitigate flood disasters in the downstream in flood events of the target scale.

However, the progress of river improvement works is not always fast, rather often delayed and slow, due to financial or societal constraints. In such a case, the flood discharge capacity of the target river is not sufficient for the designed flow rates in some of the river sections due to the lack in cross section or levee height. The areas on the banks of those section of the river remain prone to floods and can be suffered from frequent inundation by flood events smaller than the designed level. In case that reservoirs for flood control have already been constructed in the upstream of those rivers, they can be used to prevent or mitigate such frequent flood inundation caused by the small- or medium-scale flood events. In such a case, flood control operation rules of the reservoir are often changed to regulate more water so that it can further decrease water discharge to the downstream river. However, more flood water is stored in the reservoir with such operation, and reservoir storage can rapidly increase during flood control. This may increase flood risks in large-scale flood events, because reservoir can quickly reach the full storage volume and lose its flood control function in the middle of the flood event. This can result in a rapid increase in the river water level in the downstream when the reservoir stops release regulation (quick increase in water release), and can enlarge inundated areas compared to the case where the reservoir is operated with the original designed flood control rules (with smaller release regulation), as it was seen in floods widely occurred in the western Japan in July, 2018 (Nohara et al., 2019).

Various academic and practical studies have been conducted on designing the optimal reservoir operation rules for flood control taking those risks in flood control operation. Valeriano et al. (2010) developed an algorithm to optimize reservoir operation (release-inflow ratios) during flood season by use of a distributed hydrologicalmodel. Connaughton et al. (2014) analyzed the effects of simplified flood reservoir operation rules when different types of hydrographs were applied. Mateo et al. (2014) assessed the impacts of reservoir operation on flood inundation that occurred in the downstream of the Chao Phraya River Basin, Thailand, in 2011. Bruwier et al. (2015) analyzed the operation rules of a multi-reservoirs system in order to identify an effective operation method of those reservoirs under the hydrological condition after climate change.

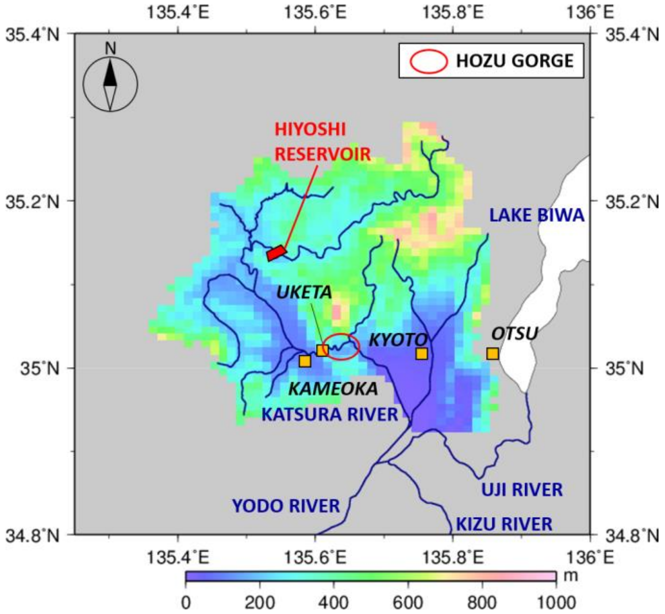

**Figure 1**. Location and elevation of the target river basin.

Real-time hydrological forecasts were also often considered to advance flood control operation of reservoirs in many studies (e.g., Wang et al., 2012; Masuda & Oishi, 2013). However, forecasts inevitably contain some uncertainty, thus reservoir operation based on a hydrological forecast may bring an adverse impact to the downstream in case the forecast is missed. Although hydrological forecast models keep being updated and gradually increasing potential advantages in real-time decision making for flood control operation of reservoirs, it is still important to identify a simple reasonable flood control operation rule with which the release rate can be determined only by observed reservoir states (e.g., inflow, storage) in case the forecast considered is not so reliable.

An approach to estimate a reasonable flood control policy of the reservoir is to consider a minimization problem of the expected annual flood damage for various scales of flood scenarios with the examined operation policies. However, a method has not yet been established to determine the most effective reservoir operation rules for flood control considering both small-scale but frequent floods and rare but large-scale floods, balancing flood inundation damages as a result of reservoir operation under various flood scenarios in a quantitative manner. As it is expected that extreme flood events may occur more frequently under the changing climate, it is getting more and more important to develop an effective approach to optimize flood control operation policy of existing reservoirs with consideration of its potential risks under the extreme flood conditions.

Considering the circumstances described above, this study aims at developing a method to analyze the effectiveness and impacts of reservoir operation policy for flood control based on rainfall-runoff-inundation analysis in order to identify the optimal policy for reservoir flood control considering various flood scenarios with different scale and pattern. The paper shows an example of the analysis on the effects of flood control policies of the Hiyoshi Reservoir, which is located in the upper Katsura River in Japan, under extreme flood conditions.

## 2 METHODOLOGY

### 2.1 Target area and reservoir

The target area is the upper Katsura River, one of the three major tributaries of the Yodo River in Japan. Figure 1 shows the location and elevation of the target river basin. The length and drainage area of the Katsura River is 107 km and 1,159 km$^2$, respectively, until it joins the Yodo River. In the middle stream of the Katsura River, there is a gorge area which is called as Hozu Gorge, which is located between Kyoto City and Kameoka City. There is also a relatively low land area around Kameoka in the upstream of the Hozu Gorge, where it is called as the upper Katsura River basin. This area has been suffered from frequent flood inundation from the Katsura River because river water level can easily be raised due to the bottleneck effect of the Hozu Gorge.

There is a multi-purpose reservoir, which is called Hiyoshi Reservoir, in the upstream of Kameoka. The catchment area of the reservoir is 290 km$^2$, and it is operated for flood control, water supply and power generation. The reservoir was originally designed to control flood events of up to 100-year return period with its flood control capacity (42 million cubic meters (MCM) in the flood season), so that it can protect its downstream areas including Kameoka, the western part of Kyoto, and other cities located on the banks of the Yodo River. The reservoir inflow rate to start regulation of release rate from the reservoir (flood control) was 300 m$^3$/s, and the maximum release rate from the reservoir during flood events was set to be 500 m$^3$/s in the original flood control policy, as a part of the river management plan of the Yodo River basin.

However, river improvement works (enlarging river cross sections by enlarging levees for example) was delayed in the upper Katsura River Basin, and river cross sections in this area are not sufficient to pass all the water through without inundation if the Hiyoshi Reservoir released water of its maximum release rate (500 m$^3$/s). Considering this situation, the flood control operation policy of the Hiyoshi Reservoir has been changed to prevent frequent flood inundation around Kameoka in the upper Katsura River basin. The inflow rate to start flood control operation has been changed to 150 m$^3$/s, and maximum release rate during flood control has also been changed to 150 m$^3$/s. Thanks to this change in the flood control policy of the Hiyoshi Reservoir, frequency of inundation has notably been reduced around Kameoka. This, however, means that the reservoir stores flood water much more than originally designed, which means it is prone to lose its flood control function by getting full storage volume due to the flow regulation during large scale floods. The reservoir actually lost its flood control function in the middle of flood events in September in 2013 and July in 2018.

### 2.2 Outline of the proposed method

Firstly, rainfall scenarios are generated. This can be done by deriving observation data from historical heavy rainfall events in the target river basin or by artificially generating pseudo hyetographs by use of stochastic approaches. Heavy rainfall which can cause large-scale floods must be included in the target rainfall scenarios. The return period of each rainfall scenario is also estimated through a flood frequency analysis. Rainfall-runoff analysis in the target river basin is then conducted with the generated rainfall scenarios. Inundation analysis is also coupled with the rainfall-runoff analysis, so that it can represent flood inundation process as well as exchange of water between the river channels and floodplains, which affects the amount of water going to the downstream section of the river. Reservoir flood control operation is also modelled and incorporated into the rainfall-runoff-inundation analysis, so that changes in the inundation process can be analyzed when the flood control rules of the reservoir are changed. The impacts of reservoir flood control on inundation is then evaluated by considering inundation depth, coverage and duration as well as economic loss according to the spread of inundation and property distribution for each reservoir operation policy under each flood scenario. The results of impact analysis are aggregated considering frequency and impact of each flood control case so as to identify the optimal policy of reservoir operation for flood control.

### 2.3 Generation of rainfall scenarios for rainfall-runoff-inundation analysis

Various methods have been developed for generation of heavy rainfall scenarios. One of the typical ways to gain heavy rainfall scenarios is to derive hyetographs from historical heavy rainfall events. This approach is widely used because there is no necessity to assume the scale or spatio-temporal pattern of rainfall. One drawback of this approach is that the number of observed heavy rainfall events is often limited because heavy rainfall does not occur so frequently. This is usually the case when extreme rain events are generated. In that case, one can increase the total amount of historical rainfall to a certain scale by multiplying the rainfall value at each time step by a same value (greater than 1.0). This means that the generated rainfall scenario has the same spatio-temporal pattern with the original historical rainfall scenario.

On the other hand, simulated generation of rainfall scenarios is also effective when historical records long enough to conduct a rainfall frequency analysis with a good accuracy is available. For instance, when the probabilistic distribution which annual maximal rainfall values follow is known, rainfall value of any return period can be generated in a stochastic manner. When annual maximal basin-averaged rainfall values follow a Gumbel distribution $f(\mu, \eta)$ as defined by the following equation,

$$f(\mu,\eta)=\frac{1}{\eta}\exp\left(-\frac{x-\mu}{\eta}\right)\exp\left[-\exp\left(-\frac{x-\mu}{\eta}\right)\right] \quad [1]$$

one can generate values of annual maximal basin-average rainfall from the following equations:

$$X=\mu-\eta\ln(-\ln Y) \quad [2]$$

where X is a random value that follows a Gumbel distribution $f(\mu, \eta)$, and Y is a uniform random value from 0 to 1. One can get a number of values for annual maximal basin-average rainfall from small values to large ones by repeating this random sampling. This enables a Monte Carlo approach in analyzing the effect of each flood control operation policy of the target reservoir by increasing the number of input sets for the rainfall-runoff-inundation analysis. While the total rainfall amount can artificially be generated in this fashion, spatio-temporal distribution of rainfall can be derived from historical rainfall events.

## 3 RAINFALL-RUNOFF-INUNDATION MODEL

### 3.1 Outline of rainfall-runoff-inundation model

For the rainfall-runoff-inundation analysis to estimate the impacts of flood control operation of the reservoir, the two dimensional (2D) Rainfall-Runoff-Inundation (RRI) model developed by Sayama et al. (2012), a distributed rainfall-runoff-inundation model, was employed in this study. The RRI model can simulate the rainfall-runoff and inundation processes, and is capable to analyze the interaction between those processes in an integrated manner without coupling with other hydrological or hydraulic models. The basic theory employed in the RRI model for simulating surface flow is 2D shallow water equations, which can be defined by the following equations (Sayama et al., 2012):

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=r-f \qquad [3]$$

$$\frac{\partial q_x}{\partial t}+\frac{\partial u q_x}{\partial x}+\frac{\partial v q_x}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho_\omega} \qquad [4]$$

$$\frac{\partial q_y}{\partial t}+\frac{\partial u q_y}{\partial x}+\frac{\partial v q_y}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{\tau_y}{\rho_\omega} \qquad [5]$$

where, $h$ is the height of water from the local surface, $q_x$ and $q_y$ are respectively the unit width discharges in $x$ and $y$ directions, $u$ and $v$ are respectively the flow velocities in $x$ and $y$ directions, $r$ is the rainfall intensity, $H$ is the height of water from the base level, $\rho_w$ is the density of water, $q$ is the gravitational acceleration, $\tau_x$ and $\tau_y$ are respectively the shear stresses in $x$ and $y$ directions, respectively. The RRI model also employs diffusion wave approximations, which simplifies Eqs. [4] and [5] by ignoring inertial terms as the following equations:

$$q_x=\frac{1}{n}h^{\frac{5}{3}}\sqrt{\left|\frac{\partial H}{\partial x}\right|}\operatorname{sgn}\left(\frac{\partial H}{\partial x}\right) \qquad [6]$$

$$q_y=\frac{1}{n}h^{\frac{5}{3}}\sqrt{\left|\frac{\partial H}{\partial y}\right|}\operatorname{sgn}\left(\frac{\partial H}{\partial y}\right) \qquad [7]$$

where sgn(·) is the signum function. In order to deal with surface and subsurface flows in an integrated manner, Eqs. [6] and [7] are again replaced in the RRI model by the following equations assuming the saturated subsurface flow based on Darcy's law:

$$q_x=\begin{cases}-kh\dfrac{\partial H}{\partial x} & (h\le d)\\[2ex] -\dfrac{1}{n}(h-d)^{\frac{5}{3}}\sqrt{\left|\dfrac{\partial H}{\partial x}\right|}\operatorname{sgn}\left(\dfrac{\partial H}{\partial x}\right)-k(h-d)\dfrac{\partial H}{\partial x} & (h>d)\end{cases} \qquad [8]$$

$$q_y=\begin{cases}-kh\dfrac{\partial H}{\partial y} & (h\le d)\\[2ex] -\dfrac{1}{n}(h-d)^{\frac{5}{3}}\sqrt{\left|\dfrac{\partial H}{\partial y}\right|}\operatorname{sgn}\left(\dfrac{\partial H}{\partial y}\right)-k(h-d)\dfrac{\partial H}{\partial y} & (h>d)\end{cases} \qquad [9]$$

where, $k$ is the lateral saturated hydraulic conductivity and $d$ is the void in the soil which can be calculated by multiplying the soil depth by the effective porosity, respectively. On the other hand, flow in the river channel is calculated with the 1D diffusion wave approximation ($q_y$=0 in Eq. [7]). See Sayama et al. (2012) for the further details of the RRI model.

### 3.2 Setup of the RRI model for the upper Katsura River basin

The upper river basin of the Katsura River is modelled by use of the RRI model. The most downstream point of the modelling was set to Uketa, which is located just upstream the Hozu Gorge (Figure 1). Data for the basin modelling, Japan Flow Direction Map developed by Yamazaki et al. (2018) was used in this study. The dataset provides data of elevation and flow direction in Japan areas with the resolution of 30 meters. Those data are upscaled to model the basin with the cell size of 150 meters so as to reduce the calculation time for simulation. The model was calibrated using observed data of historical flood events. The Nash-Sutcliff model efficiency coefficient for inflow of the Hiyoshi Reservoir ranged from 0.88 to 0.92 for historical large-scale flood events.

**Table 1**. Rainfall scenarios considered in the case study.

| Scenarios | Rainfall events from which data derived | Maximum 24-hour rainfall | Return periods (24h rainfall) | Maximum 48-hour rainfall | Return periods (48h rainfall) | Temporal pattern of rainfall |
|---|---|---|---|---|---|---|
| **A** | Frontal rain (Jul. 2018) | 277 mm | 30 years | 410 mm | 80 years | Multiple peaks |
| **B** | Typhoon Man-yi (Sep. 2013) | 304 mm | 80 years | 337 mm | 30 years | Single peak at the middle |
| **C** | Typhoon Tokage (Oct. 2004) | 169 mm | 5 years | 224 mm | 5 years | Late single peak |
| **D** | Frontal rain (Sep.1989) | 181 mm | 5 years | 197 mm | 3 years | Multiple peaks |
| **E** | Frontal rain (hypothetical) | 294 mm | 200 years | 497 mm | 400 years | Multiple peaks |

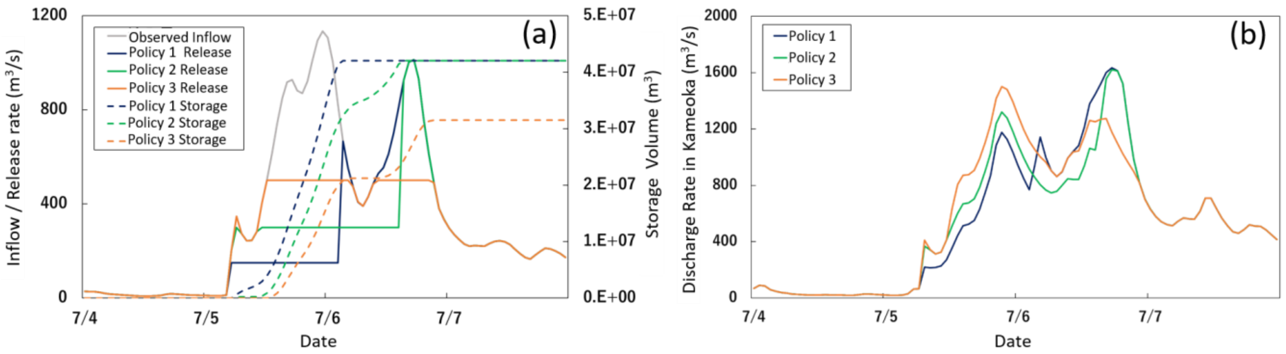

**Figure 2**. Comparison of the effects of flood control operation policies for Scenario A on: (a) reservoir operation, and (b) river discharge at Kameoka.

## 4 CASE STUDY

### 4.1 Settings of analysis

As the preliminary study on the effects of flood control operation policies of the Hiyoshi Reservoir on flood inundation in the upper Katsura River basin, three kinds of flood control policy were investigated in this study. Two hypothetical flood control policies were considered. One is the operation policy where the maximal release rate is 300 $m^3$/s unless reservoir storage is full (Policy 2), and the other is that where the maximal release rate is 500 $m^3$/s (Policy 3). The current flood control policy where the maximum release rate is 150 $m^3$/s was also considered in this analysis for comparison (Policy 1).

Five rainfall scenarios as shown in Table 1 were considered in this case study. Four of them were derived from historical heavy rainfall events with different scales and patterns (Scenarios A to D), and the other was artificially generated based on Scenario A by adding another rainfall peak after the last peak of Scenario A.

Flood damage due to inundation was estimated considering economic losses in agriculture and house properties. Economic losses were calculated by multiplying the unit monetary losses by the inundated area and depth calculated through the inundation analysis using the RRI model.

### 4.2 Results

Example of the simulation results on flood control operation of the reservoir is shown in Figure 2. The figure shows the comparison in the effects of each operation policy on reservoir states (Figure 2(a)) and those on water level of the Katsura River at Kameoka point (Figure 2(b)) in Scenario A. It can be seen in Figure 2(a) that reservoir operation with Policies 1 and 2 released water as much as reservoir inflow at the final peak of inflow because reservoir storage became full before that peak due to their regulation of release to small values (150 $m^3$/s and 300 $m^3$/s, respectively). On the other hand, reservoir operation with Policy 3, which allows to release water up to 500 m$^3$/s, did not make reservoir storage full, and flood control was also conducted at the final peak of inflow. Thanks to this operation, the maximum water level of the Katsura River at Kameoka point was reduced to a smaller value at the second peak of discharge, while it was relatively high at the first peak of discharge due to greater release from the reservoir. The maximum river water level at Kameoka was, however, lower with Policy 3 than those with other operation policies because flood control operation was still conducted at the second peak with Policy 3. On the contrary, the maximum river water level at Kameoka point was high with Policies 1 and 2 due to the loss in flood control function of the reservoir at the second peak of discharge, which can enlarge inundation and flood damages.

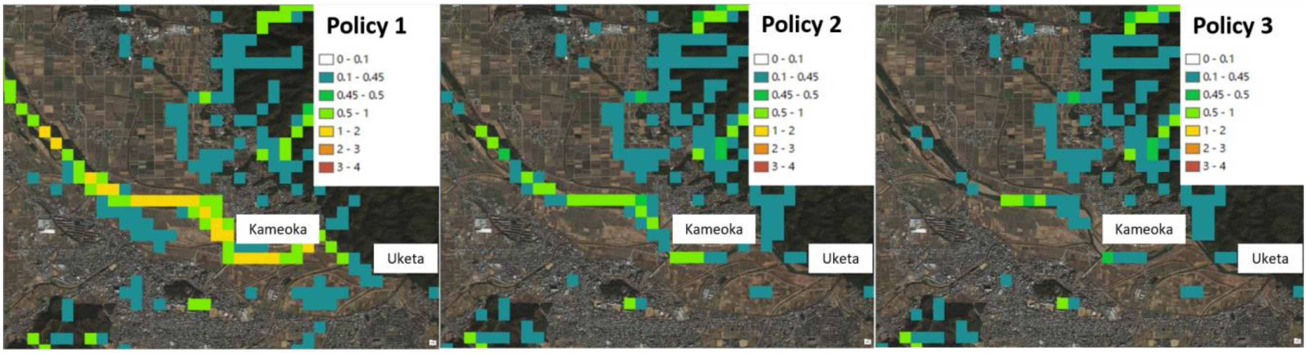

**Figure 3**. Results of the maximum inundation depth (in meters) for each operation policy for Scenario A.

**Table 2**. Flood damages (in billion JPY) calculated through the inundation analysis with flood control polices.

| SCENARIOS | POLICY 1 | POLICY 2 | POLICY 3 |
|---|---|---|---|
| **A** | 16.93 | 16.92 | 15.95* |
| **B** | 15.45* | 17.15 | 21.62 |
| **C** | 4.48* | 4.73 | 5.44 |
| **D** | 8.48* | 8.48* | 8.52 |
| **E** | 30.91 | 30.91 | 28.57* |

Examples of estimation results of the maximum inundation depth for Scenario A under each policy of reservoir operation for flood control is shown in Figure 3. It can be seen in this figure that the distribution of maximum inundation depth changes depending on the reservoir operation policies. The inundated area becomes wide as the release regulation of the reservoir gets larger, especially in case Policy 1 with the regulation of 150 m$^3$/s was applied where the reservoir storage became full and started water release as much as reservoir inflow in the earlier time.

Estimation results of flood damages for each rainfall scenario were summarized in Table 2. It can be seen in this table that Policy 3 has an advantage for flood events with greater return period of 48-hour rainfall while Policy 1 showed less damage in flood events with smaller return period. Although the return period of 24-hour rainfall of Scenario B is relatively long (80 years), reservoir operation for flood control with Policy 1 mitigated flood damage more than that with Policies 2 or 3 where the reservoir can release more water. Because Scenario B is a kind of quick floods, which has a sharp peak but does not last long. Therefore, the total amount of water to be stored in the reservoir was relatively small (30-year return period for 48-hour rainfall) even though the rainfall intensity is high around the peak of rainfall.

### 4.3 Discussions

The result of the impacts of each operation policy for flood control of the reservoir evaluated in the previous process must be aggregated in order to identify an optimized operation policy considering various kinds of floods. One of the typical approaches in such a case is to consider the expected annual damage due to inundation for each flood scenario considering its occurrence probability. The optimal operation policy can be derived by minimizing the sum of the expected annual damages of all flood scenarios among the considered operation policies. However, a number of flood scenarios with different scales or spatio-temporal distributions are needed for this method. Approaches with synthetic generation of rainfall scenarios are therefore considered to be useful for such a method unless there are long historical records of rainfall observation available in the target river basin.

Seeing only the expected annual flood damages may overlook other information, such as expected flood damage in rainfall scenarios with a return period concerned. In that case, it is more convenient for understanding more detailed risk reduction tendency to draw a flood risk curve for each operation policy of reservoir operation for flood control. Figure 4 shows a concept of changes in flood risk curve when different operation policies of a reservoir are applied. The difference in flood damage with any frequency of flood occurrence can easily be compared between two operation policies of the reservoir from this figure. Although the flood control policy focusing on large-scales floods does not mitigate flood damage very much in small-scale floods, it mitigated flood damage greatly in large-scale floods. This characteristics is important and should not be overlooked, because flood mitigation is needed more in large-scale flood events where flood damage can be catastrophic, rather than in small-scale flood events where flood damage is mild and sometimes becomes acceptable with other countermeasures. Development of a method to optimize flood control policy of a reservoir using such a flood risk curve analysis is one of the next steps of this study.

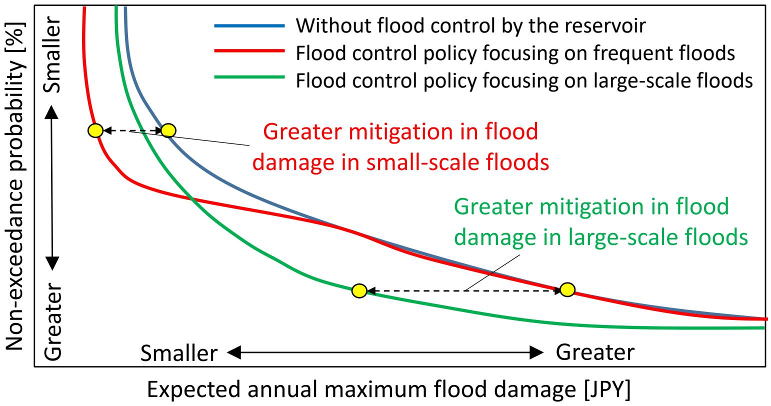

**Figure 4**. Concepts of the change in flood risk curve when different reservoir flood control policies are applied.

## 5 CONCLUSIONS

In this study, a method was proposed for optimization of reservoir's flood control operation based on inundation analysis in the downstream considering extreme flood scenarios. River discharge, inundation area and depth in the target river basin are then estimated for the considered rainfall scenarios using the RRI model, a rainfall-runoff-inundation model. Optimal reservoir operation for flood control was analyzed from results of the inundation analysis of the considered extreme flood scenarios. Through the case study applied to the Hiyoshi Reservoir in the Upper Katsura River in Japan, optimal flood control strategy of the reservoir was respectively identified for each scenario of extreme flood event. Development of a method to aggregate the results of impact analysis of each flood control policy by use of the concept of flood risk curves will be the next step of this study.

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