EFFECTIVE RESERVOIR OPERATION FOR FLOOD CONTROL BASED ON RAINFALL-RUNOFF-INUNDATION ANALYSIS CONSIDERING EXTREME EVENTS IN THE KATSURA RIVER BASIN, JAPAN

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ABSTRACT

Recently, extreme flood events have become more frequent in Japan. As the progress of river improvement works is often behind schedule, the flow capacity of rivers is often insufficient. In such cases, flood control rules of the upstream reservoirs have been changed to address small or medium scale floods, which occur more frequently, by regulating the release discharge rate to lower values than that originally designed. During large flood events, however, the water level of such reservoirs could rapidly increase and, due to their restricted release rate, reach the full storage level. This situation puts the reservoirs in the danger of losing their flood control function during floods. In this study, effects of flood control operation rules for various patterns of rainfall scenarios, including large floods, were evaluated using rainfall-runoff-inundation analysis, in order to identify an effective operation policy for flood risk reduction. Taking the upper Katsura River in Japan as a target basin, optimal operation rules of the Hiyoshi Reservoir for flood control were estimated in terms of river discharge, water level, inundated area, and economic damage.

1 INTRODUCTION

In recent years, heavy rainfall events caused severe flood disasters frequently in Japan. In July 2018, heavy frontal rain hit western Japan and caused severe flood and sediment disasters in wide areas. This rainfall event broke records of 24-hour, 48-hour and 72-hour rainfall in many rain gauge stations (Japan Meteorological Agency 2018). Flood control operation was conducted by many reservoirs in river basins affected by heavy rainfall, and this greatly mitigated the downstream inundation. However, rainfall and inflow were so much that the reservoir storage capacity for flood control was used up in eight reservoirs during this flood event. Those reservoirs therefore carried out the emergency spillway gate operation where water as much as inflow is released from reservoirs to prevent further increase in reservoir water level (Ministry of Land, Infrastructure, Transport and Tourism 2018, Sumi et al. 2019). This means that the reservoir lost its flood control function in the middle of floods, and resulted in severe flood inundation and human damage in downstream areas of some of those reservoirs.

Four out of those eight dams were operated to deal with small or medium scale floods by regulating their release discharge to smaller values than those originally designed in order to prevent frequent inundation in their downstream areas. This operation of a reservoir can often be seen in river basins where river improvement works have not been completed in downstream areas and flow capacity in rivers is not as much as the designed discharge volume. This operation, however, can increase the risk of severe flood inundation in case of large floods. Because the reservoir stores water more than designed during a flood, water stored in the reservoir increases to the full storage volume faster than designed. This means that there is more chance for the reservoir to lose its flood control function especially during large floods, which can result in severer inundation in the downstream than that when original reservoir operation is applied due to less flood control by the reservoir. Thus it is necessary for more comprehensive flood risk management to understand the impact of changes in reservoir operation on inundation risk in its downstream areas.

In the concern that extreme floods may occur more frequently in the future due to climate change, various studies on real optimization of reservoir flood control considering hydrological forecasts have been carried out to develop an effective reservoir operation method for flood control (e.g., Wang et al. 2012, Masuda & Oishi 2013). However, forecasts essentially contain some uncertainty, which makes it difficult to implement those theories into practice because all the stakeholders may not know in advance how the reservoir is operated in each flood event. Prior release, which allows a reservoir to increase flood its control capacity on a temporary basis before floods, is also one of the strategies to use existing reservoirs effectively. Various methods have been proposed to decide the timing and volume of prior release based on observed or forecasted rainfall (Amai et al. 2014, Inomata et al. 2018). However, the flood control capacity enhanced by prior release is still not sufficient for extreme large flood events where total inflow volume to be stored in the reservoir as flood control exceeds its effective storage capacity. It is therefore important to identify a robust reservoir operation policy for flood control which can also be effective to mitigate flood inundation in the downstream in large flood events.

Considering the circumstances mentioned above, this work aims at analyzing impacts of flood control operation rule for various scales of floods including large flood scenarios using rainfall-runoff-inundation analysis as a fundamental study to identify effective operation policy for flood risk reduction in the downstream. The proposed method is applied to the upper Katsura River basin in Japan, where a reservoir is operated to regulate much water for flood control due to insufficient flow capacity of the downstream river sections.

2. TARGET BASIN AND RESERVOIR

2.1 Target basin

The target basin is the upper reaches of the Katsura River, which is one of tributaries of the Yodo River in Japan (Fig. 1). The length and drainage area of the Katsura River are respectively 107 km and 1159 km^2. There is a gorge area in the middle reach of the Katsura River, which is called Hozu Gorge. Kameoka City, which is located just upstream of the Hozu Gorge, has been suffered from frequent inundation from the Katsura River because of the bottleneck effect of the gorge (Fig. 2). Because Kameoka City lies on the basin (called Kameoka Basin), runoff water tends to concentrate around this city from the surrounding mountains during floods. The small outlet of the basin constrained by the Hozu Gorge makes water drainage more difficult, which leads to frequent inundation from this river in Kameoka City.

The river improvement has been planned in 1990 to be carried out in a step-by-step manner according to the master plan (target flood return period: 100 years), medium-term action plan (30 years), and immediate action plan (10 years). River improvement works corresponding to the first immediate action plan for the return period of 10 years were completed in 2009, and gradual excavation of high water channel was finished in 2017 (Kyoto Prefecture 2018). The flow capacity in rivers are, however, not enough and floods occur frequently, for example, in Typhoon Tokage in 2004, Typhoon Man-yi in 2013, and heavy rain in July 2018.

On the other hand, the existing levees of the Katsura River compose the open levee system in Kameoka City (Fig. 3). Levees are lowered around the confluences of tributaries with the Katsura River in this levee system. When the water level of the Katsura River becomes high during floods, water from the Katsura River naturally comes to the land side of the levees over the lower sections, and the water is stored because the land side is lower land. These land is mainly used for agriculture. After floods, the water goes out of the levees quickly and this can reduce the inundation damage.

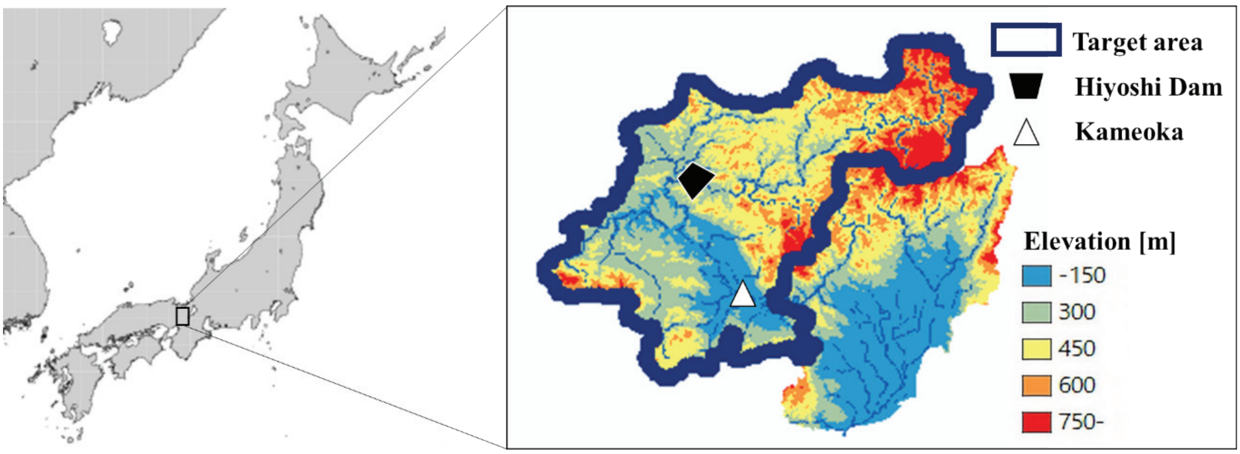

Figure 1 : The Katsura River basin.

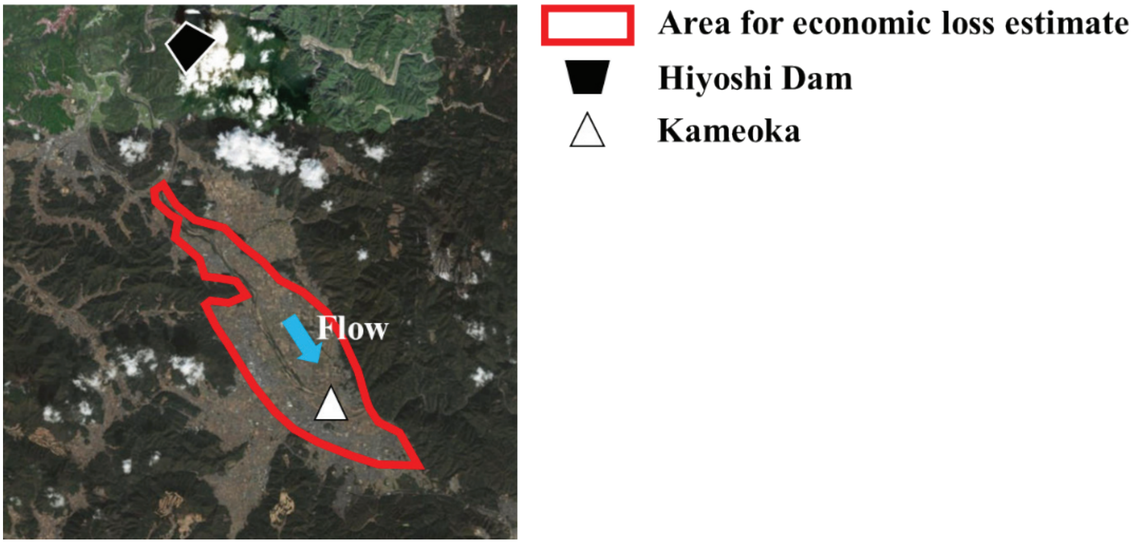

Figure 2 : The area for economic loss estimate.

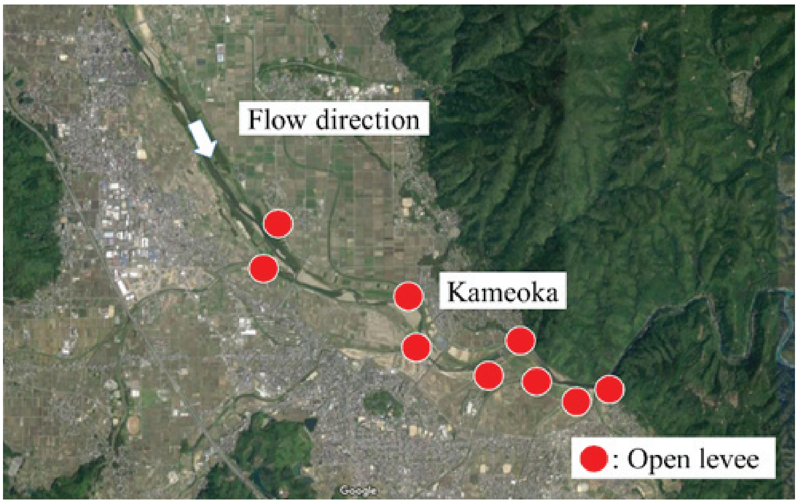

Figure 3 : The open levees along the Katsura River in Kameoka City.

2.2 Target reservoir

There is a reservoir, the Hiyoshi Reservoir, in the upstream of the Katsura River. This reservoir is a multi-purpose reservoir with the catchment area of 290 km^2, and operated by Japan Water Agency mainly for flood control, water supply, and power generation. The reservoir was originally designed to control floods of 100-year return period. However, the target return period has been changed to 20 years as described below because the downstream river improvement work is not completed. Table 1 lists specifications of the Hiyoshi Reservoir, while Table 2 and Figure 3 show the original and current flood control policies of the reservoir.

The details of the current operation rule of the Hiyoshi Reservoir for flood control was determined as below (Michiba 2010). The flow capacity of the Katsura River at Uketa, which is located at the outlet of Kameoka Basin (just upstream of the Hozu Gorge), was equivalent to flood discharge of only four-year return period just after the reservoir was constructed. Therefore, operation rules of the reservoir effective for small- or medium-scale floods, which occur more frequently, were needed. His calculation showed that a rule employing 300 m^3/s constant release could mitigate inundation damage in the downstream more than the original rule of 300 m^3/s to 500 m^3/s constant release and constant rate. However, this rule cannot mitigate the inundation damage when large rainfall occurs in the downstream tributaries that join the Katsura River between the dam and Uketa, because the catchment area of those tributaries (727 km^2) is 2.5 times larger than that of the Hiyoshi Reservoir (290 km^2). Furthermore, the flow capacity in the downstream area including Kameoka City which had often been suffered from inundation damage was small. Hence the reservoir operation policy for smaller floods was accepted. In the investigation in Michiba (2010), he calculated total inundation area and the number of inundated houses in the downstream area including Kameoka City changing the designed level of floods from five-year.

Table 1 : Specification of the Hiyoshi Reservoir.

The Hiyoshi Reservoir	
Purposes	Flood control, water supply, and power generation
Effective storage capacity	58,000,000 m^3
Flood control capacity	42,000,000 m^3 (in flood seasons)
Catchment area	290 km^2
Dam type	Concrete gravity
Height	67.4 m
Length	438 m
Year of completion	1998

Table 2 : The original and current flood control policies of the Hiyoshi Reservoir.

	Original	**Current**
Maximum designed inflow rate (Return period)	2200 m^3/s (100 years)	1510 m^3/s (20 years)
Gate operation rule for flood control	constant release & constant rate	constant release
Inflow rate to start flood control	300 m^3/s	150 m^3/s
Maximum designed release rate	500 m^3/s	150 m^3/s

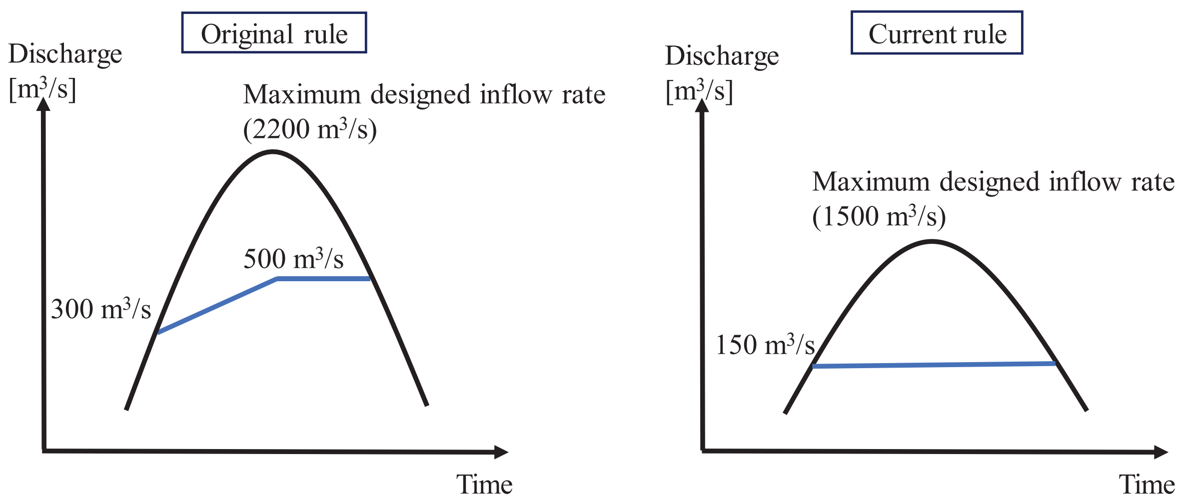

Figure 3 : The original and current rule of the Hiyoshi Reservoir for flood control.

to 100-year return period and maximal release rate from the reservoir among 0, 100, 150, 200 and 300 m^3/s. The results showed 100, 150 and 200 m^3/s constant release rule were better than the others in terms of inundated houses, and 100 m^3/s release rule was the best in terms of the total inundated area. However, inundation damage in some area is larger in 100 m^3/s release rule than in the original rule, so 150 m^3/s constant release rule was adopted as the best flood control policy in order to mitigate inundation damage in the downstream areas.

Figure 4 shows operation results of the Hiyoshi Reservoir for flood control with current operation rules for floods caused by Typhoon Man-yi in September 2013 (Fig. 4A) and for floods due to heavy frontal rainfall in July 2018 (Fig. 4B). In the typhoon in 2013, the inflow rate (1694 m^3/s) topped the highest record since the reservoir was constructed in 1998, and even exceeded the designed maximum inflow rate (1510 m^3/s). Although the emergency spillway gate operation started in the end of the flood because the reservoir became nearly full, the maximum water level of the Katsura River was lowered by 1.5 m at Kameoka (a water level observation point) than when the Hiyoshi Reservoir did not control floods.

On the other hand, in the heavy rain in July 2018, there were four inflow peaks, and the emergency spillway gate operation started before the last peak came. Thus the reservoir could not control the last peak of the flood. This suggests that when there was another peak after the last peak, or the last peak was much greater, flood inundation damage could be larger in the downstream areas due to a greater rate of release from the reservoir.

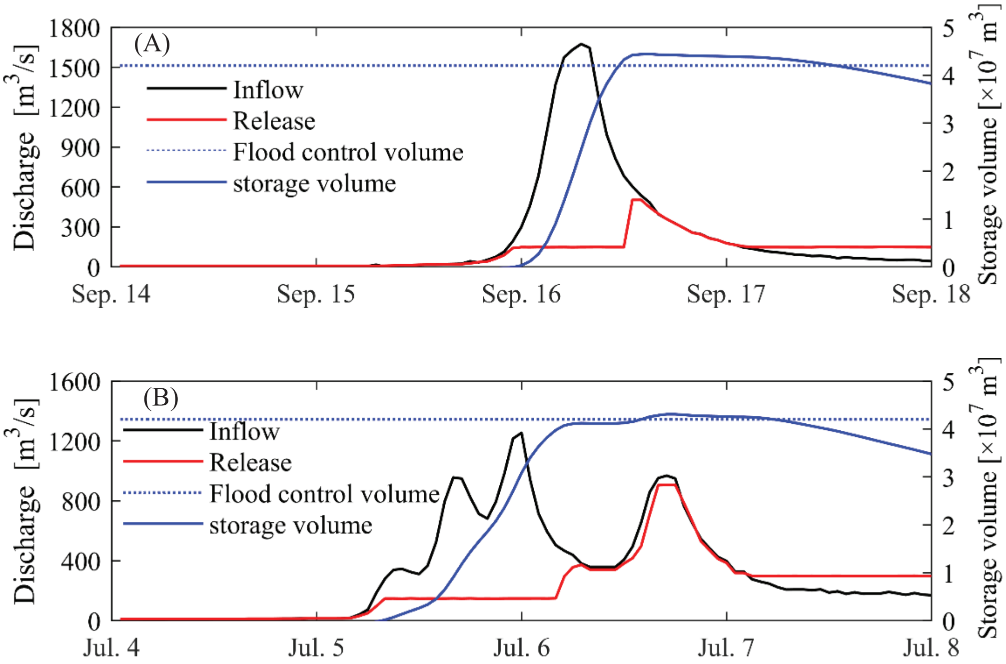

Figure 4 : Flood control operation of the reservoir, (A) for floods due to Typhoon Man-yi in September 2013, and (B) for floods due to frontal rain in July 2018.

3. METHODOLOGY

3.1 Outline of proposed method

Firstly, rainfall scenarios were generated based on historical rainfall events including large-scale ones. Rainfall-runoff-inundation analysis of the target basin was then conducted using Rainfall-Runoff-Inundation (RRI) model developed by Sayama et al. (2012). Operation of the Hiyoshi Reservoir was also modelled in this analysis. Operation rule of the reservoir for flood control was changed to analyze the downstream discharge, water level, inundation area and economic loss in order to analyze impacts of the policies of the reservoir on the downstream area.

3.2 Rainfall scenarios

Seven rainfall scenarios were generated based on historical rainfall data in the target area. We picked up four events with different spatio-temporal patterns and return periods from rainfall events that caused inundation in Kameoka City. In addition, three hypothetical hyetographs were also generated based on those of historical rainfall events. The details of scenarios are shown in Table 3. Hypothetical 1 was generated based on frontal rain in July 2018, by adding another rainfall peak in the last. Hypothetical 2 and Hypothetical 3 were both generated by stretching the hyetograph in the flood event caused by Typhoon Man-yi in September 2013. The maximum 48-hour rainfall of Hypothetical 2 corresponds with that of frontal rain in July 2018, while Hypothetical 3 and Hypothetical 1 have the equivalent amount of 48-hour rainfall.

Table 3 : The rainfall scenarios for case study.

Scenarios	Maximum 24h rainfall [mm]	Maximum 48h rainfall [mm]	Return period (24h rainfall) [year]	Return period (48h rainfall) [year]	Temporal pattern
A. Frontal rain (Sep. 1989)	181	197	5	3	Multiple peaks
B. Typhoon Tokage (Oct. 2004)	169	224	5	5	Late single peak
C. Typhoon Man-yi (Sep. 2013)	304	337	80	30	Middle single peak
D. Frontal rain (Jul. 2018)	277	410	30	80	Multiple peaks
E. Frontal rain (Hypothetical 1)	294	497	200	400	Multiple peaks
F. Typhoon (Hypothetical 2)	371	412	200	80	Middle single peak
G. Typhoon (Hypothetical 3)	457	506	400	400	Middle single peak

3.3 Setting up the RRI model for the upper Katsura River Basin

In this study, Rainfall-Runoff-Inundation (RRI) model by Sayama et al. (2012) was employed for the rainfall-runoff-inundation analysis. This model is a two-dimensional model capable of simulating rainfall-runoff and flood inundation simultaneously. Japan Flow Direction Map developed by Yamazaki et al. (2018) was used as the data for basin modeling. This is a surface flow direction datasets at 1 s (~ 30 m) resolution for the entire Japan domain. This data was upscaled to the cell size of 150 m in this study in order to reduce the calculation time. The model was calibrated using observed data of a historical flood event in September 2013. The Nash-Sutcliff model efficiency coefficient for inflow of the Hiyoshi Reservoir was 0.92. Figure 5 shows the results of simulated using calibrated parameters and observed inflow rate.

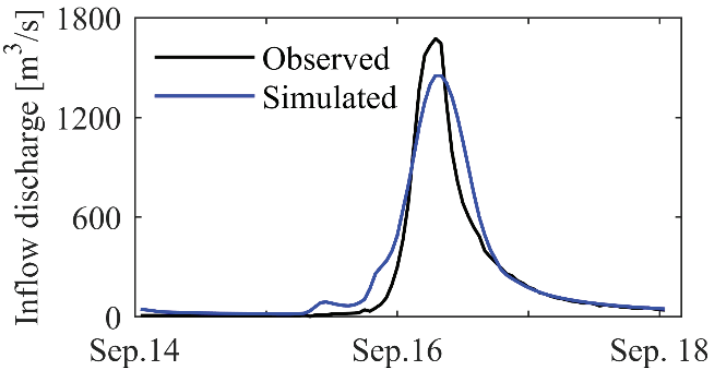

Figure 5 : Simulated and observed inflow of the Hiyoshi Reservoir in Typhoon Man-yi in 2013.

4. RESULTS OF CASE STUDY

Table 4 shows the maximum release rate from the reservoir, the maximum water level at the water level observation point and inundation area in Kameoka City, and Table 5 shows difference of economic loss between 300 m^3/s or 500 m^3/s release rule, and 150 m^3/s release rule. The economic loss was calculated based on the guideline for estimation of economic loss caused by flood inundation (Ministry of Land, Infrastructure, Transport and Tourism 2005).

Table 4 : Results of case study

Rainfall scenarios release rate	**150 m^3/s**			**300 m^3/s**			**500 m^3/s**		
	Max water level [m^3/s]	**Max area rate** [m]	**Inundated release level** [km^2]	**Max water rate** [m^3/s]	**Max area level** [m]	**Inundated release** [km^2]	**Max water** [m^3/s]	**Max area** [m]	**Inundated** [km^2]
A	150	5.0	8.62	300	5.4	8.91	500	5.9	9.92
B	150	5.8	7.22	300	6.1	8.06	500	6.5	9.43
C	1056	7.1	13.79	598	7.3	14.56	500	7.7	16.74
D	924	6.8	19.13	924	6.8	19.13	500	6.5	18.65
E	1176	8.5	20.43	1176	8.5	20.43	1176	8.3	20.39
F	1750	8.7	20.36	1490	8.3	20.05	1137	8.5	20.23
G	2252	10.1	20.75	2167	9.8	20.75	2021	9.7	20.75

Table 5 : The economic loss of case study.

Scenarios	**150 m^3/s Economic loss [108 JPY]**	**300 m^3/s Economic loss [108 JPY]**	**500 m^3/s Economic loss [108 JPY]**
A	49.0	49.6 (+0.6*)	51.3 (+2.4*)
B	38.7	42.3 (+3.6*)	47.3 (+8.7*)
C	75.4	90.2 (+14.8*)	122.4 (+47.0*)
D	120.9	120.9 (0*)	115.7 (-5.2*)
E	304.1	304.1 (0*)	271.9 (-32.2*)
F	405.9	245.2 (-160.7*)	266.9 (-139.0*)
G	701.6	648.8 (-52.8*)	586.7 (-114.8*)

* Difference from the economic loss in 150 m^3/s release rule.

Figure 6 shows simulation results of inflow, release discharge, and storage volume of the Hiyoshi Reservoir and water level at Kameoka for Scenario D. It can be seen in Figure 6 that emergency spillway gate operation started later in 300 m^3/s constant release rule than in 150 m^3/s constant release rule, and this delayed a rapid increase in river discharge at Kameoka. In 500 m^3/s constant release rule, emergency operation was not conducted, and the maximum river discharge at Kameoka was the smallest in these three operation rules.

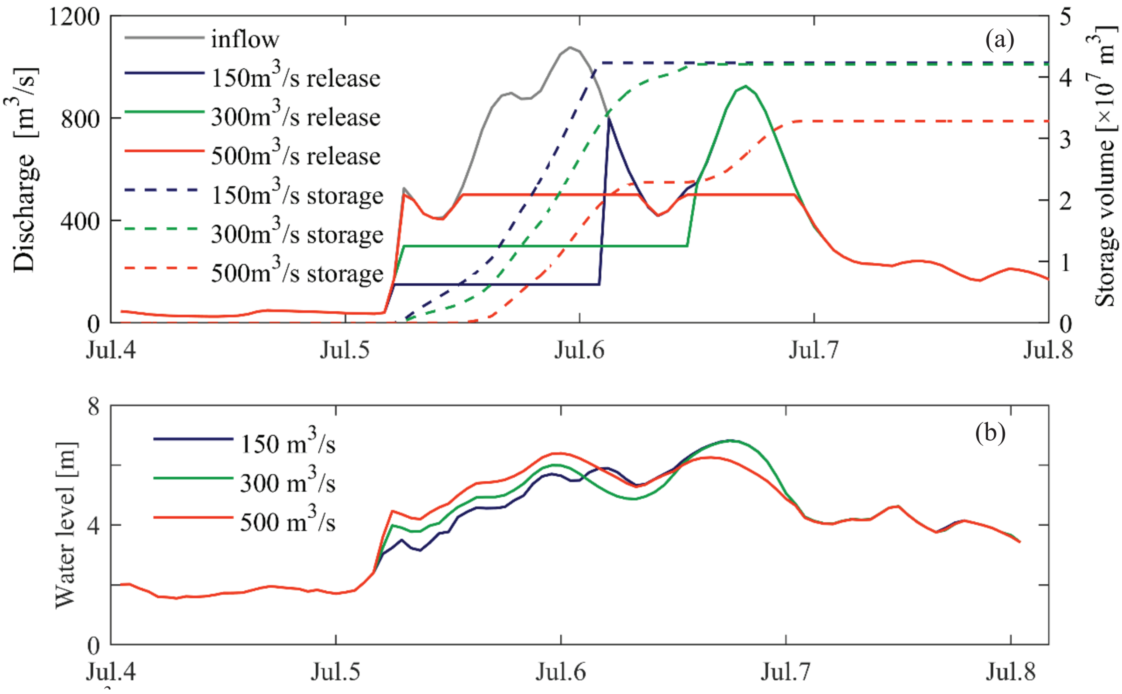

Figure 6. Simulation results of: (a) inflow, release discharge, and storage volume of the Hiyoshi Reservoir, and (b) water level at Kameoka for Scenario D.

Simulated inundation depth and area in Kameoka City in Scenarios E and G are shown in Figure 7. In Figure 7, the Katsura River flows in the red-colored areas. Although the return periods of both of Scenario E (Hypothetical 1) and Scenario G (Hypothetical 3) are 400 years, they have different temporal patterns: Scenario E has multiple flow peaks while Scenario G has a simple peak. The difference in inundation area among each release policy was smaller for Scenario E than for Scenario G. This indicates that the storage in the reservoir became full during a flood in a scenario with multiple rainfall patterns even the return period was the mostly same as a scenario with a single peak.

In Scenario F (Hypothetical 2), the river discharge at Kameoka was the smallest in 300 m^3/s constant release rule. Comparing with 150 m^3/s and 500 m^3/s release rules, the river discharge was the mostly same with both rules as shown in Figure 8. However, the river water level at Kameoka was lower by 0.2 m with 150 m^3/s release rule than that with 500 m^3/s release rule. This suggests that the rainfall is not much in the early period in this scenario and the maximum river water level was lower with 500 m^3/s release rule in which the release discharge was larger in the early period.

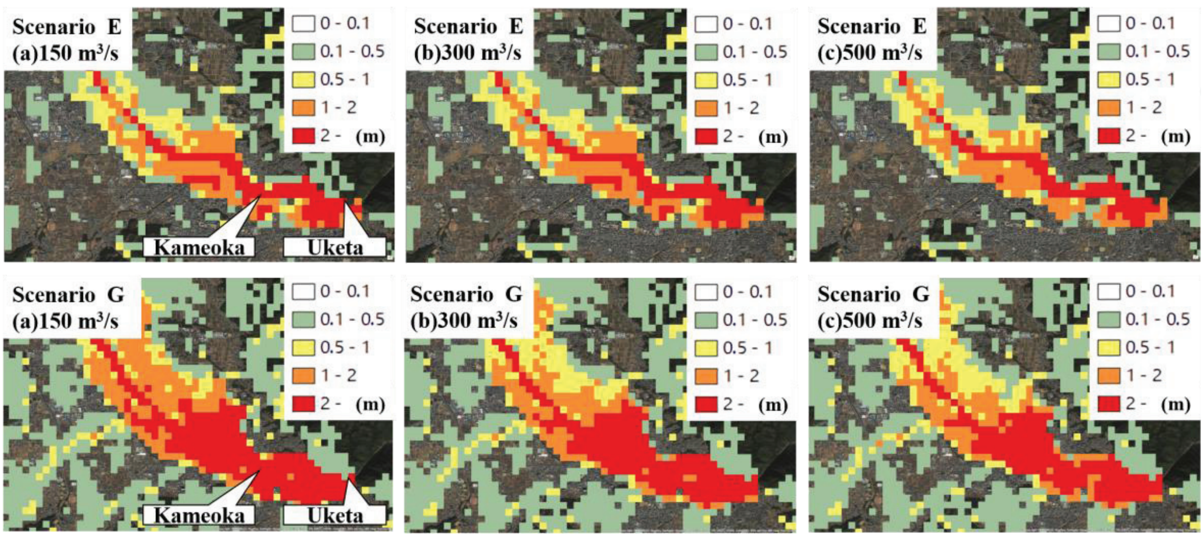

Figure 7 : Inundation area and depth in Kameoka City for Scenario E and G.

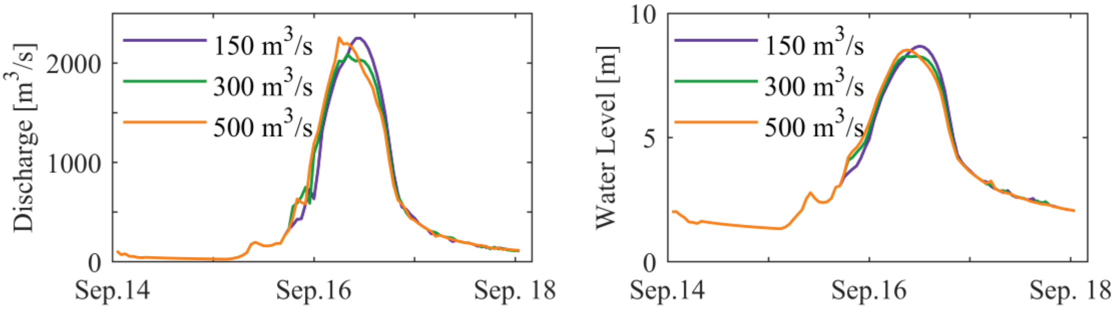

Figure 8 : The discharge and water level at Kameoka for Scenario F.

It can be seen from the results shown in Table 5 that the economic loss in Kameoka City was the smallest with 500 m^3/s release rule in large flood events which return period is around or longer than 80 years (Scenario D, E, F, and G) while 150 m^3/s constant release rule has an advantage in small or medium floods which return period is around or shorter than 30 years (Scenario A, B, and C). In the case of large floods, 300 m^3/s or 500 m^3/s release rule was more effective than 150 m^3/s release rule because the economic loss of houses increased with those rules.

5 CONCLUSIONS

In this study, we proposed a method to develop optimal reservoir operation for flood control based on inundation analysis. RRI (rainfall-runoff-inundation) model made it possible to analyze rainfall, runoff, and inundation process by one model through a whole catchment area. We analyzed changes in the downstream river discharge, water level, inundation area and economic loss when changing the inflow rate to start flood control from 150 m^3/s, 300 m^3/s, and 500 m^3/s. In large floods which return period were around or longer than 80 years, the economic loss in Kameoka City was the smallest in 500 m^3/s release rule, while in small or medium floods which return period were around or shorter than 30 years, that was the smallest in 150 m^3/s release rule. In order to analyze the impacts of reservoir operation policies on the downstream damage in detail, a number of rainfall scenarios with spatio-temporal patterns are needed. For future works, it is necessary to improve the way how to evaluate operation rule and then develop a method to optimize flood control policy.

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REFFERENCE

Amai, Y. & Nohara, D. 2014. Prior release operation of a multipurpose reservoir for flood control based on accuracy assessment of real-time hydrological prediction; *Proc. 19th IAHR-APD Congress 2014*, Hanoi.

Inomata, H., Kawasaki, M. & Kudo, S. 2018. Quantification of the risks on dam preliminary release based on ensemble rainfall forecasts and determination of operation, *Journal of Disaster Research* 13(4): 637-649.

Japan Meteorological Agency. 2018. Flash report of the heavy rainfall in July, 2018. (in Japanese)

Kyoto Prefecture. 2018. River infrastructure development project in the upstream of the Katsura River of the Yodo river system. (in Japanese).

Masuda, H. & Oishi, S. 2013. Study on optimization of the integrated dam operation using ensemble prediction in the upper reaches of the Nabari River; *Proc. 35th IAHR World Congress*.

Michiba, M. 2010. Flood control of the Hiyoshi Reservoir –flood control considering flow capacity of downstream reaches- *River engineering –technical experiences-, Kinki Regional Development Bureau*:136-153. (in Japanese).

Ministry of Land, Infrastructure, Transport and Tourism. 2018. Proposal for enhancement of flood control function of dams and dissemination of related information in preparation for more frequent extreme rainfalls. (in Japanese).

Ministry of Land, Infrastructure, Transport and Tourism. 2005. The guideline for estimation of economic loss caused by flood inundation (in Japanese).

Sayama, T., Ozawa, G., Kawakami, T., Nabesaka, S. & Fukami, K. 2012. Rainfall–runoff–inundation analysis of the 2010 Pakistan flood in the Kabul River basin. *Hydrological Sciences Journal* 57(2): 298-312.

Sumi, T., Mitsunari, M. & Hamaguchi, T. 2019. Challenges in flood control operation and dissemination of related information - Lessons from the record-breaking heavy rain in July 2018, Japan -; *Proc. 5th Asia-Pacific Group International Symposium on Dams (APG 2019)*.

Wang, F., Wang, L., Zhou, H., Valeriano, O.C.S., Koike, T. & Li, W. 2012. Ensemble hydrological prediction-based optimization of a multiobjective reservoir during flood season in a semiarid basin with global numerical weather predictions, *Water Resources Research* 48: W07520.

Yamazaki, D., Togashi, S., Takeshima, A. & Sayama, T. 2018. High-resolution flow direction map of Japan. *Annual Journal of Hydraulic Engineering, Japan Society of Civil Engineers* 74(5): 163-168.