OPTIMAL RESERVOIR FLOOD CONTROL CONSIDERING LARGE FLOODS BASED ON RAINFALL-RUNOFF-INUNDATION ANALYSIS

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ABSTRACT

Heavy rainfalls have frequently caused severe flood disasters in Japan. In order to mitigate inundation in the downstream reaches, it is important to effectively operate upstream reservoirs for flood control. The flow capacity of downstream rivers is often insufficient when the progress of river improvement works is behind schedule. In such cases, flood control rules at some of the upstream reservoirs have been changed in order to address small or medium floods that occur more frequently: the release discharge rate are set to smaller values than that originally designed. During large floods, 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. In order to overcome this situation, in this study, effectiveness of flood control policies were assessed considering varied flood scenarios. Reservoir states, river discharge, and inundation depth and area in the downstream were calculated by rainfall-runoff-inundation (RRI) model for rainfall scenarios with different scale and spatio-temporal distribution, changing flood control policies of the reservoir. Through the case study with the Hiyoshi Reservoir in the Katsura River, Japan, optimal reservoir flood control policy was identified so as to minimize the potential economic losses estimated by the simulated inundation depth and area.

Keywords: reservoir operation, flood control, inundation analysis, RRI model, extreme events

1. INTRODUCTION

In recent years, heavy rainfalls have frequently caused severe flood disasters in Japan. In July 2018, heavy frontal rain hit western Japan and caused severe flood and sediment disasters in wide areas. Flood control operation was conducted by many reservoirs in river basins affected by this heavy rainfall, and this greatly mitigated the downstream inundation. However, inflow discharge volume were so much in eight reservoirs that their storage capacities for flood control were used up during this flood. Those reservoirs therefore carried out emergency spillway gate operation (ESGO), where water as much as inflow was released from the 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 reservoirs totally lost their 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. Flood control policies had been changed to deal with smaller-scale but more frequent floods compared with those originally designed at four out of those eight reservoirs, by regulating their release discharge to smaller values. This change in 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 is therefore not as much as the designed discharge volume. This operation, however, can increase the risk of severe flood inundation in case of large floods. Water stored in the reservoir increases to the full storage volume faster than designed during such a flood, because the reservoir needs to store water much than designed. This means that those operation policies can increase risks for the reservoir to lose its flood control function especially during large floods. Once flood control capacity is totally finished like this way in large floods, especially before the peak of inflow, release can be increased dramatically, and results in wide inundation in the downstream, which can be severer than that when the original reservoir operation rule is applied. Thus, it is needed for more comprehensive flood risk management to understand the impact of changes in reservoir operation policy on inundation risk in its downstream areas.

Effective ways to mitigate flood risks in the downstream by upstream reservoirs have been investigated from both real-time and planning points of view. For example, studies on real-time optimization of reservoir operation considering hydrological forecasts have been carried out in recent years to identify the effective reservoir operation method for flood control (e.g., Wang et al., 2012; Masuda & Oishi, 2013). However, forecasts can overestimate or underestimate the hydrological condition to a large extent as they essentially contain uncertainty. Therefore, determining reservoir flood control operation in real-time relying on those hydrological forecasts may rather be less effective and result in severer flood impacts in the downstream than when a fixed flood control rule determined based on historical flood records without considering hydrological forecasts is applied as often seen in reservoir operation practices in Japan.

Another way to improve the flood control capability of a reservoir can be increasing the storage capacity for flood control. Prior release operation, which allows a reservoir to increase flood its control capacity on a temporary basis just before floods occur, can be considered as an effective way to enlarge the flood control capacity of a reservoir. A number of 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 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.

The purpose of this study is to identify an optimal reservoir operation policy for risk reduction considering both frequent, small or medium floods and occasional but large floods. In this study, rainfall- runoff-inundation analysis was conducted for the upper reaches of the Katsura River, Japan, changing flood control policies of the upstream reservoir. Reservoir states, river discharge, inundated area and depth were calculated for various rainfall scenarios including large flood events. Optimal reservoir flood control policy was then identified based on estimated economic loss by floods, inundated area and depth.

2. TARGET BASIN

This study focuses on the upper reaches of the Katsura River which is one of major tributaries of the Yodo River in Japan (Figure 1). The Katsura River drains 1,159 km^2 and flows for 107 km. There is a gorge section 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. Because Kameoka City lies on the basin (called Kameoka Basin), runoff water tends to concentrate around this city from 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 Hiyoshi Reservoir, which is a multi-purpose reservoir, is located in the upper part of the Katsura River. The reservoir is operated by Japan Water Agency mainly for flood control, water supply and maintenance flow. The reservoir was originally designed to control floods of 100-year return period. However, the target return period has been changed to 20 years because the downstream river improvement work is not completed. Table 1 shows a summary of the Hiyoshi Reservoir. The original and current flood control policies of the reservoir are shown in Table 2 and in Figure 2.

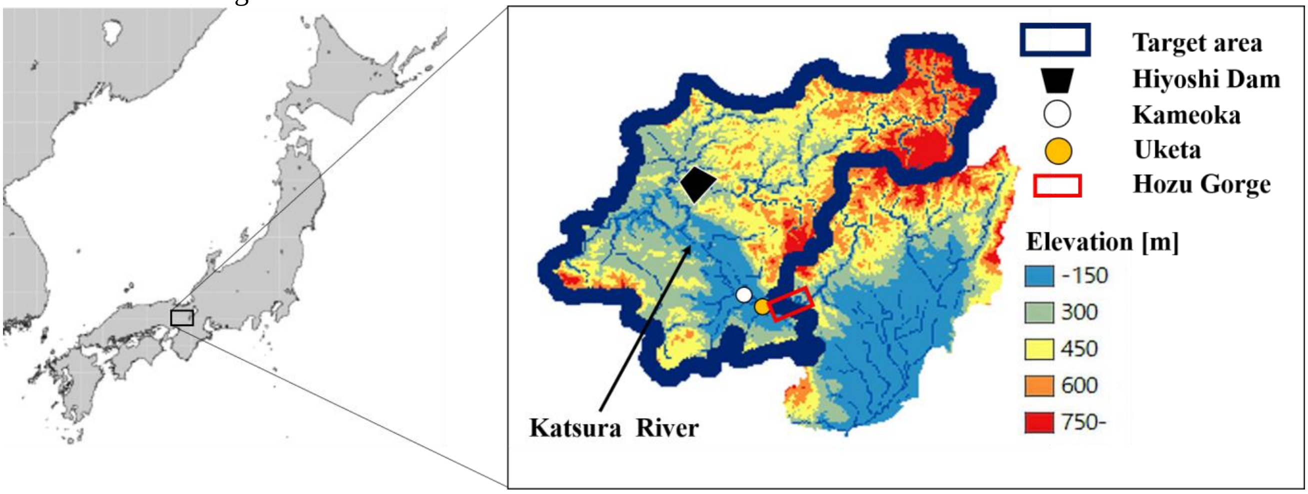

Figure 1. The Katsura River basin.

Table 1. Summary of the Hiyoshi Reservoir characteristics.

	The Hiyoshi Reservoir
Purposes	Flood control, water supply, and maintenance flow
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 of dam	67.4 m
Length of dam	438 m
Year of completion	1998

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

	Originally designed	Currently applied
Maximum designed inflow rate (return period)	2,200 m^3/s (100 years)	1,510 m^3/s (20 years)
Flood control operation type	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

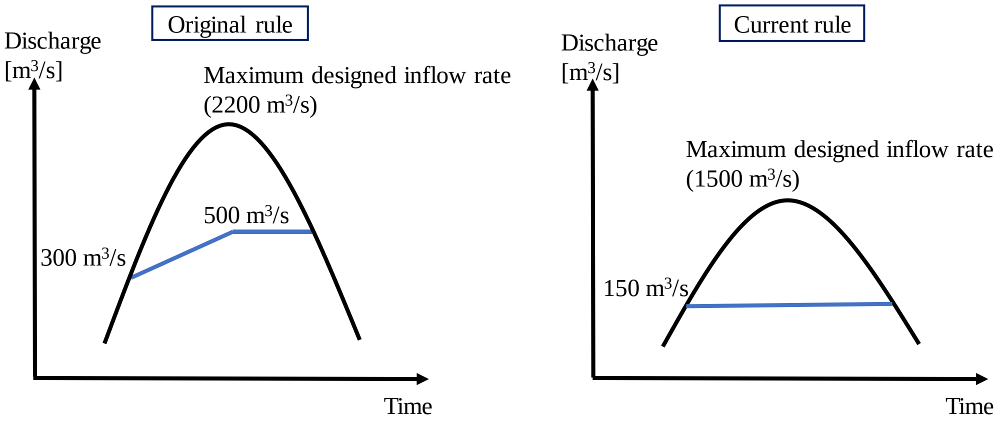

Figure 2. Original and current rule for flood control of the Hiyoshi Reservoir.

3. METHODOLOGY

3.1 Outline of proposed method

In order to analyze impacts of reservoir flood control operation in various rainfall events, firstly, rainfall scenarios were generated based on historical rainfall events including large scale events. Then, rainfall-runoff-inundation analysis was conducted for the upper reaches of the Katsura River for each generated rainfall scenarios by using Rainfall-Runoff-Inundation (RRI) model developed by Sayama et al. (2012). In large flood events, flood inundation may occur in wide areas. In order to make it possible to analyze inundation processes in those flood events, RRI model, which can simulate the rainfall-runoff and inundation processes simultaneously, was used in this study. Operation of the Hiyoshi Reservoir was also modelled in this study: the gate operation rule for flood control were constant release following the constant rule, and the maximum designed release rate was changed. In order to identify more effective flood control policy of the reservoir, downstream river discharge, water level, inundation area and economic loss were estimated. Economic loss caused by inundation for each scenario in Kameoka City was estimated based on the guideline of economic damage estimate for flood (Ministry of Land, Infrastructure, Transport and Tourism. 2005).

3.2 Modelling of rainfall-runoff-inundation process and reservoir operation

Inundation analysis was conducted considering the rainfall-runoff process by using the Rainfall-Runoff-Inundation (RRI) model developed by Sayama et al. (2012). The model is a cell grid-based distributed model, and enables to simulate rainfall-runoff and flood inundation simultaneously.

Japan Flow Direction Map developed by Yamazaki et al. (2018) was used as the input data for basin modeling. This is a surface flow direction data set with spatial resolution of one second (approximately 30 meters) resolution for the entire Japan domain. Japan Flow Direction Map can explain more exact and detailed river systems than HydroSHEDS by improving the precision of input elevation data and calculating method. In this

Table 3. Model parameters employed in this study.

Parameters	Land use A	Land use B
n [$\mathrm{m}^{-1/3}\mathrm{s}$]	0.3	0.2
d [m]	1.0	0.8
φ [-]	0.471	0.471
k_v [m/s]	-	6.540×10^{-5}
S_f [m]	-	0.1
k_a [m/s]	0.1	-
φ_u [-]	0.05	-
n_{river} [$\mathrm{m}^{-1/3}\mathrm{s}$]	0.02	0.02

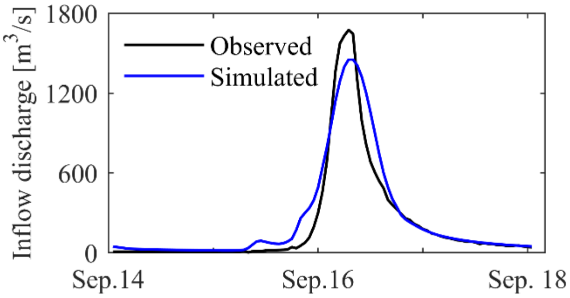

Figure 3. Simulated and observed inflow of the Hiyoshi Reservoir in Typhoon Man-yi in 2013.

study, the data was upscaled to the horizontal resolution of 150 m in order to reduce the calculation time, and the upstream basin of Uketa was modelled.

The land use of the target basin was classified into two groups: forest, waste land and golf field were classified into Land use A, while paddy field, farm land, residential area, road, railway, river and lake were classified into Land use B. Then, the model parameters, namely, Manning's roughness on slope cells [n], soil depth [d], effective porosity [φ], vertical saturated hydraulic conductivity [k_v], suction at the wetting front [S_f], lateral saturated hydraulic conductivity [k_a], unsaturated porosity [φ_u], Manning's roughness for river channel [n_{river}] are set respectively for the land uses (Table 3).

The model was validated using observed data of a historical event in September 2013. The Nash-Sutcliff model efficiency coefficient for inflow of the Hiyoshi Reservoir was 0.92. Figure 3 shows the observed inflow rate and simulated results using validated parameters. The peak inflow rate was underestimated while the total volume was slightly overestimated, and the temporal pattern was extended across the time than observed inflow. In this study, both the total volume and the peak inflow rate must be well-valanced in order to check when ESGO starts, and to analyze the river water level and inundation in the downstream areas.

4. RESULTS OF CASE STUDY

The effects of flood control policy of the Hiyoshi Reservoir on flood damages in the downstream were investigated as a case study. Four rainfall events with different spatio-temporal patterns and return periods were chosen from historical flood records for the case study (Scenarios A, B, C, and D in Table 4). All these four events caused inundation in Kameoka City. In addition, three hypothetical rainfall scenarios were generated based on historical rainfall events (Scenarios E, F, and G in Table 4). Table 4 shows a summary of those rainfall scenarios. The maximum 24-hour and 48-hour rainfalls [mm], 24-hour and 48-hour return periods [year], and temporal pattern of these rainfall scenarios are shown in Table 4. Scenario E was generated based on frontal rain in July 2018 (Scenario D), by adding another rainfall peak in the last. Scenarios F and G were both generated by stretching the hyetograph observed in Typhoon Man-yi in September 2013 (Scenario C). The maximum 48-hour rainfall of Scenario F corresponds to that of frontal rain in July 2018, while Scenarios G and E have the equivalent amount of 48-hour rainfall which is much more than historical record.

The results of estimated flood damages when each flood control policy was applied were shown in Table 5. It can be seen from Table 5 that the economic loss was the smallest with 500 m^3/s release rule in large flood events with return period more than 80 years (Scenarios D, E, F and G), whereas 150 m^3/s release rule was the most effective in small or medium flood events with return period less than 30 years (Scenarios A, B and C). This means that in large flood events (Scenarios D, E, F and G), flood control capacity in the reservoir was used up and the discharge rate suddenly increased up to approximately same value as the inflow rate (conducting ESGO), and river discharge in the downstream increased rapidly. In Scenario C, flood control capacity was used up and ESGO was also conducted (Figure 4(a)) with 150 m^3/s release rule. However, ESGO started in the final phase

Table 4. The rainfall scenarios for the case study.

	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

Table 5. The results of estimated economic loss due to flood inundation.

Scenarios	Economic loss (Difference from when 150 m^3/s release applied) [billion JPY]		
	150 m^3/s	300 m^3/s	500 m^3/s
A	4.9	5.0 (+0.1)	5.1 (+0.2)
B	3.9	4.2 (+0.4)	4.7 (+0.9)
C	7.5	9.0 (+1.5)	122 (+4.7)
D	12.1	12.1 (±0)	11.6 (-0.5)
E	30.4	30.4 (±0)	27.2 (-3.2)
F	40.6	24.5 (-16.1)	26.7 (-13.9)
G	70.2	64.9 (-5.3)	58.7 (-11.5)

of the flood event where inflow rate already became smaller after the peak, and the maximum release rate was not so much. Thus, the maximum river water level at Kameoka was a little higher with 150 m^3/s release rule than with 500 m^3/s release rule (Figure 4(b)), and the economic loss was smaller with 150 m^3/s release rule than with 500 m^3/s release rule (Table 5). In small flood events (Scenarios A and B), the maximum release discharge rate was the greatest with 500 m^3/s, because ESGO was not conducted with any release rule considered in this study.

Figures 4 and 5 show simulation results for Scenarios C and G, respectively. In Scenario C shown in Figure 4 (a), the reservoir storage got full during the flood event, and ESGO was conducted with 150 m^3/s and 300 m^3/s release rule while ESGO was not conducted with 500 m^3/s release rule. With 150 m^3/s or 300 m^3/s release rule, however, the operation started in the final phase of the flood, and the maximum release discharge was not so great. Thus, the maximum river water level at Kameoka was smaller with 150 m^3/s release rule than with 500 m^3/s release rule (Figure 4 (b)). In contrast, in Scenario G shown in Figure 5 (a), the reservoir capacity for flood control was used up with any release rules, and the maximum release discharges were extremely larger than those in Scenario C. As can be seen in Figure 5 (b), the maximum river water level was the highest with 150 m^3/s release rule.

Figure 6 shows the number of inundated cells for Scenarios C and G. In this figure, the inundation depth was aggregated into the following categories: less than 0.5 m (corresponding to inundation depth below the ground floor level of houses), from 0.5 m to 3.0 m (corresponding to inundation depth above the ground floor level), and more than 3.0 m (corresponding to inundation of the second floor level of houses). In Scenario C, the inundated area became wider as the release discharge volume increased, because the river water level at Kameoka was the highest with 500 m^3/s release rule as shown in Figure 4 (b). In Scenario G, the inundated area with each release rule were approximately same. However, the number of cells with inundation depth deeper (or more) than 1.0 m became smaller with 500 m^3/s release rule, corresponding to the results in maximum river water level at Kameoka which was smallest with 500 m^3/s release rule as shown in Figure 5 (b). The number of cells inundated deeper than 1.0 m was 739 out of 949 inundated cells when 150 m^3/s release was employed, 647 out of 948 with 300 m^3/s, and 556 out of 947 with 500 m^3/s release rule. These results indicate that 500 m^3/s release rule can mitigate not only inundation damage but also human loss in larger flood events like Scenario G, because that release rule decreased the number of cells inundated more than 1.0 m, where it is difficult to evacuate. Therefore, in this case study, the economic loss due to inundation damage was smallest with 150 m^3/s release rule in small flood events, because ESGO was not conducted. In contrast, in large flood events, 500 m^3/s release rule was the most effective for mitigation economic loss at Kameoka. This is because the flood control capacity was used up in large flood events, and the maximum release discharge was greater when 150 m^3/s release rule was applied. In addition, the number of cells with inundation depth deeper than 1.0 m was smallest with 500 m^3/s release rule. This means that this flood control rule has more advantage in supporting flood evacuation of residents than the other release rules by mitigating deep inundation in large floods.

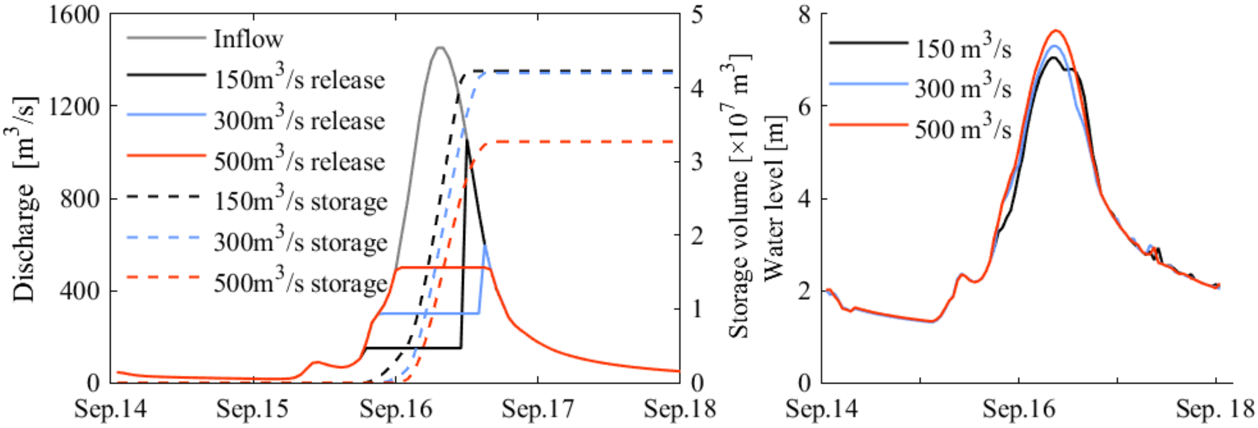

Figure 4. Simulation results for Scenario C: (a) inflow and release discharge of the Hiyoshi Reservoir, and (b) water level at Kameoka.

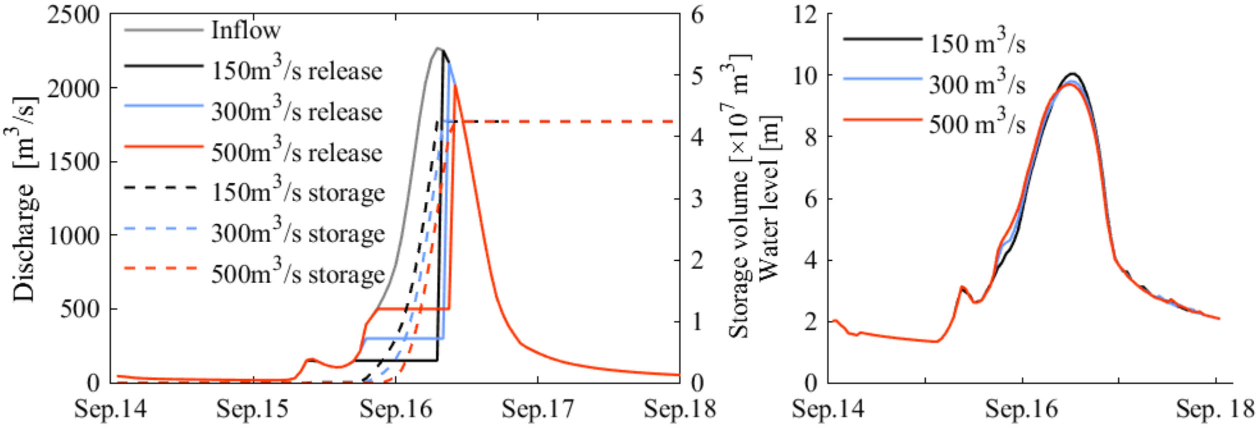

Figure 5. Simulation results for Scenario G: (a) inflow and release discharge of the Hiyoshi Reservoir, and (b) water level at Kameoka.

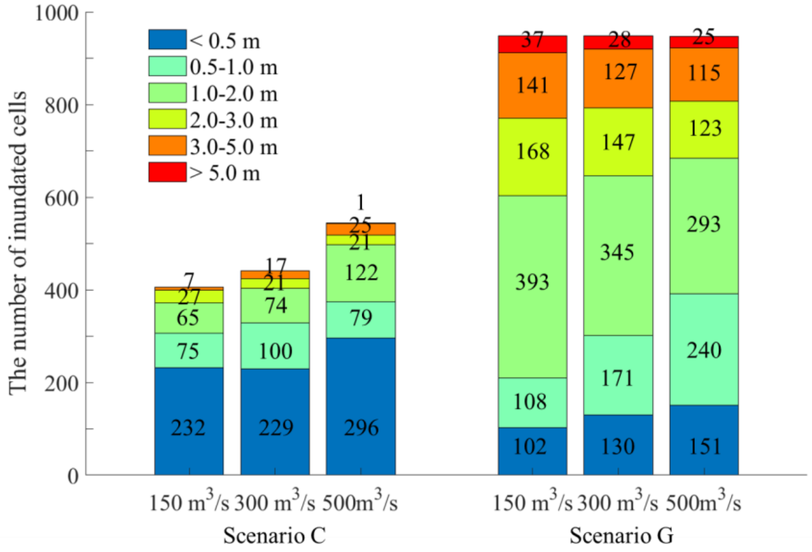

Figure 6. The number of inundated cells for Scenarios C and G.

5. CONCLUSIONS

In this study, we proposed a method to develop optimal reservoir operation for flood control based on rainfall-runoff-inundation analysis. RRI (rainfall-runoff-inundation) model made it possible to analyze rain-fall, runoff, and inundation process simultaneously. We analyzed changes in the downstream river discharge, water level, inundation area and economic loss when changing the maximum designed release rate from 150 m^3/s, to 300 m^3/s and 500 m^3/s. In small flood events, the economic loss due to inundation damage was smallest with 150 m^3/s release rule, because ESGO was not conducted in any release rule. In contrast, 500 m^3/s release rule was the most effective for mitigation economic loss at Kameoka in large flood events. This is because the flood control capacity was used up in large flood events, and the maximum release discharge was greater with 150 m^3/s release rule in those flood events. In addition, the number of cells with inundation depth deeper than 1.0 m was smallest with 500 m^3/s release rule. This means that this flood control rule has more advantage in supporting flood evacuation than the other release rules by mitigating deep inundation in large floods. In order to analyze the impacts of reservoir operation policies on the downstream damage in more detail, a number of rainfall scenarios with spatio-temporal patterns are needed. As future works, it is also necessary to improve the way how to evaluate operation rule in order to develop a method to optimize flood control policy of reservoirs.

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REFERENCES

Amai, Y. and 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. and 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.

Masuda, H. and 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.

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. and 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. and 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. and 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. and Sayama, T. (2018). High-resolution flow direction map of Japan. *Annual Journal of Hydraulic Engineering, Japan Society of Civil Engineers* 74(5): 163-168.