

## **A STUDY ON THE APPLICATION OF CASCADE TYPE FLOOD CONTROL TO THE CHIKUGO RIVER**

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### **ABSTRACT**

The efficiency of the "Cascade" method based on a new flood-control concept was verified in a river basin. In recent years, an increase in the frequency and intensity of disaster hazards, such as heavy rainfall, has been observed in Japan, presumably due to global warming. Additionally, environmental preservation in Japan has continued to be respected even after rapid and high economic growth. However, it is extremely difficult to implement large-scale public works because budgets for such projects have been reduced. We therefore recommend the construction of multiple small-scale dams around river basins instead of a single large-scale dam in order to prevent flood disasters and preserve the natural environment. In this study, Cascade-type flood control was demonstrated using numerical simulation in which an upstream dam arranged in a series overflows from an emergency spillway while a final downstream dam is required only to use its normal spillway and never its emergency spillway. The Cascade method should strengthen the flood control capability for the lower reaches of a river, which are generally more important than the upper reaches. This study clearly demonstrated that the Cascade method of flood control is much more effective than the conventional method in the Chikugo River. Additionally, the Cascade method, which combines dams in series and in parallel, is also effective for improving the efficiency of multiple dams operated cooperatively.

**Keywords:** Flood control, dam, Cascade method, overflow, Chikugo River

### **1 INTRODUCTION**

In recent years, an increase in the frequency and intensity of disaster hazards, such as heavy rainfall, drought, and typhoons, has been observed in Japan, presumably due to global warming. Various effects of global warming are expected to become apparent in the future; for example, the occurrence of catastrophic disasters due to large-scale floods is feared, as mentioned by the Science Council of Japan (2008). Social and disaster-prevention infrastructure in Japan was often constructed during earlier periods of strong economic growth, and most of it is aging. Although national resilience in the face of disaster has recently become a pressing issue following the Great East Japan Earthquake in 2011, it is unlikely that the new construction or major overhauls of large-scale disaster prevention facilities will continue in the long-term, due to worldwide economic conditions. Therefore, intelligent disaster prevention measures, such as the effective use of existing facilities, will be increasingly needed in the future.

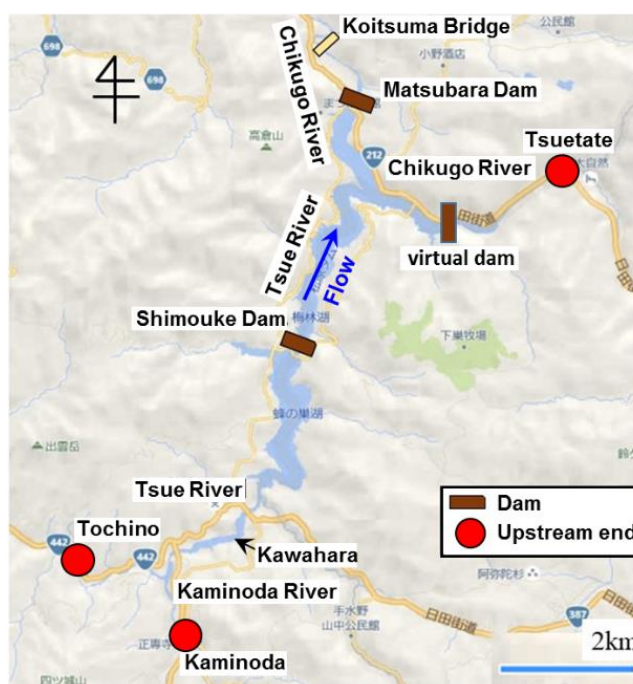
It is necessary to simultaneously cope with the increasing risk of natural disasters and preserve the natural environment. Large-scale public works projects such as dam construction have become extremely difficult to implement in Japan due to a significant reduction in funding for public works except for that urgently required for disaster recovery and reconstruction following the 2011 earthquake disaster and concerns over the environmental impact of such projects. Therefore, small-scale infrastructure is considered to be important in the future.

Under such circumstances, Oshikawa et al. (2013) proposed a new flood control concept, called the "Cascade" method, which allows dams to overflow through each emergency spillway in a basin with dams constructed in series. The conventional concept of flood control using multiple dams, even when constructed in series, deems each design high water discharge equivalent to harmless discharge for a design magnitude flood and never uses emergency spillways. Oshikawa et al. (2013) compared the flood control effects of multiple dams constructed in series based on the conventional concept with those based on the new Cascade concept. Using numerical simulations, they clarified that the ability to control flooding in the downstream area, which is generally more important than in the upstream area, is significantly enhanced by using emergency spillways at upstream dams located in mountainous areas.

Studies on the Cascade method have previously been conducted based on numerical simulations and laboratory experiments using an idealized straight channel with a uniform slope (Oshikawa et al., 2013; Oshikawa et al., 2015; Oshikawa and Komatsu, 2015). However, since Cascade-type flood control allows for overflow through each emergency spillway, it will drastically change the conventional concept of flood control; however, flood control effects on actual rivers must be evaluated in order to put it to practical use. Therefore, in this study, Cascade-type flood control was applied to the Chikugo River basin, which has multiple dams, and the effects were verified based on one-dimensional unsteady flow analysis. Additionally, in order to improve the efficiency of the cooperative operation of multiple dams, the flood control effects of the Cascade method in which dams are combined in series and in parallel were also examined, with the inclusion of a new virtual dam in the Chikugo River basin.

## 2 METHODOLOGY

The hydrodynamic simulation software MIKE 11 was used for this study (DHI, 2009). The study area used for the computation, shown in Figure 1, is 11 km of the Chikugo River (km 89 to 100, from Koitsuma Bridge to the village of Tsuetate), 12.2 km of a tributary of the Tsue River (from the confluence point to the village of Tochino in the Tsue River basin), and 1 km of the Kaminoda River, which is a tributary of the Tsue River. The area is assumed to have no water inflow (including rainfall) other than that from the upstream region.



**Figure 1.** Study area used for the computation, in the upper reaches of the Chikugo River basin.

Two dams have been built in the study area: the Shimouke Dam (height, 98 m; flood control capacity, 51.3 million m<sup>3</sup>), on the upstream side of the confluence point of the Tsue River; and the Matsubara Dam (height, 83 m; flood control capacity, 45.8 million m<sup>3</sup>), on the Chikugo River downstream of the Tsue River's confluence. In this study, we investigated the maximum outflow discharge from the Matsubara Dam, which is almost equivalent to the peak flow discharge at the downstream end (Koitsuma Bridge), in order to evaluate the flood control effects through the cooperative operation of these two multipurpose dams.

## 3 APPLICATION OF CASCADE-TYPE FLOOD CONTROL TO A REAL RIVER BASIN

In this section, which describes Cases A1-A4, the flood control effect of the Cascade method was verified in the Chikugo River with dams constructed in series by using one-dimensional unsteady flow analysis. For simplicity, we assumed that the only flood inflow point was Tochino on the upstream side of the Shimouke Dam (see Figure 1).

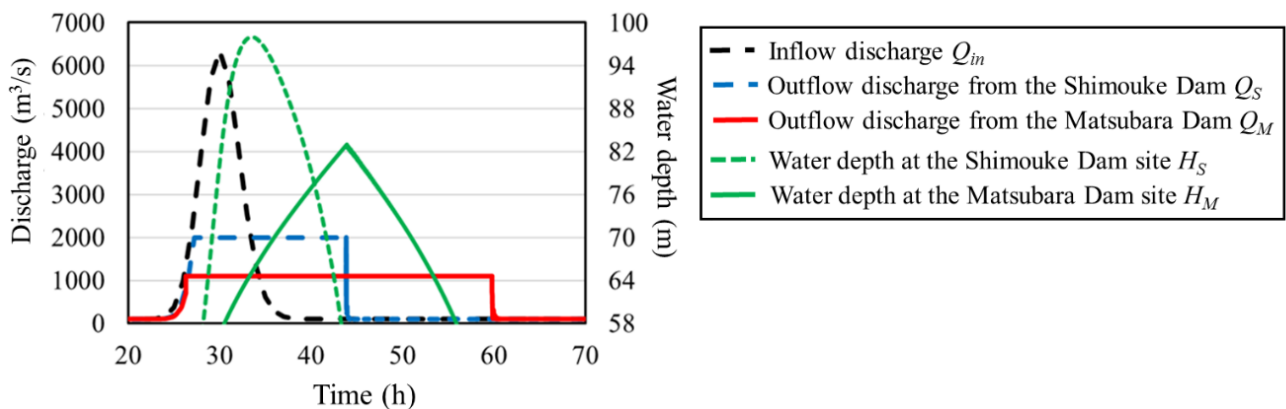
As the boundary condition for the upstream end, the following Eq. [1] was used to set the inflow discharge  $Q_{in}(t)$  generated at Tochino:

$$Q_{in}(t) = Q_b + (Q_p - Q_b) \left\{ \frac{t}{t_p} \exp \left( 1 - \frac{t}{t_p} \right) \right\}^c, \quad [1]$$

where  $Q_p$  is the maximum inflow discharge,  $t_p$  ( $=30$  h) is the arrival time of  $Q_p$ ,  $Q_b$  ( $=100$  m<sup>3</sup>/s) is the ordinary water discharge,  $c$  ( $=200$ ) is a constant related to the shape of the hydrograph, and  $t$  is time, as described in *Hydraulics Formulae* (JSCE, 2002).

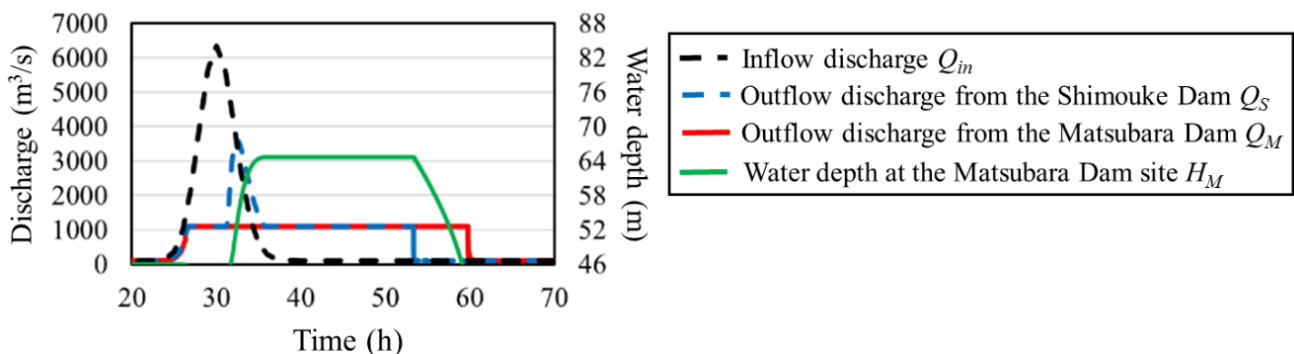
Based on the conventional flood control for a hypothetical scenario used in Cases A1-A4, design flood discharge  $Q_p$  for the Chikugo River basin and design high water discharge ( $Q_{ai}$ ) equivalent to the harmless discharge from each dam were calculated as Case A1. The subscript “ $i$ ” ( $= 1, 2$ ) indicates the dam number from the upstream side, with the subscript “1” denoting the Shimouke Dam and “2” denoting the Matsubara Dam. The actual design high water discharge value ( $Q_{a2}=1100$  m<sup>3</sup>/s) was used for the Matsubara Dam. The values of  $Q_p$  and  $Q_{a1}$  in which water depths just upstream of each dam are equal to the height of each dam were determined by trial and error, when the maximum outflow discharges from each dam were equal to each design high water discharge  $Q_{ai}$  under the condition of fixed model parameters  $c$ ,  $Q_b$ , and  $t_p$  in Eq. [1] to keep the shape of the inflow hydrograph constant. In Case A1, the optimum peak inflow discharge  $Q_p$  as the upstream boundary condition and the design high water discharge for the Shimouke Dam  $Q_{a1}$ , were found to be 6339 and 1996 m<sup>3</sup>/s, respectively.

Figure 2 shows the discharges from the Shimouke Dam and Matsubara Dam ( $Q_S$  and  $Q_M$ , respectively) and the water depths just before the Shimouke Dam and Matsubara Dam ( $H_S$  and  $H_M$ , respectively) for the inflow discharge  $Q_{in}$  where  $Q_p = 6339$  m<sup>3</sup>/s in the conventional Case A1. In this figure, the maximum outflow discharge from the Shimouke Dam  $Q_{Smax}$  is equal to 1996 m<sup>3</sup>/s (the same as  $Q_{a1}$ ), and the maximum value of  $H_S$  is equal to 98 m (the levee height of the Shimouke Dam). Additionally, the peak discharge from the Matsubara Dam  $Q_{Mmax}$  is equal to 1100 m<sup>3</sup>/s (the same as  $Q_{a2}$ ), and the maximum value of  $H_M$  is equal to 83 m (the height of the Matsubara Dam). Therefore, the conventional flood control is properly performed in Case A1.



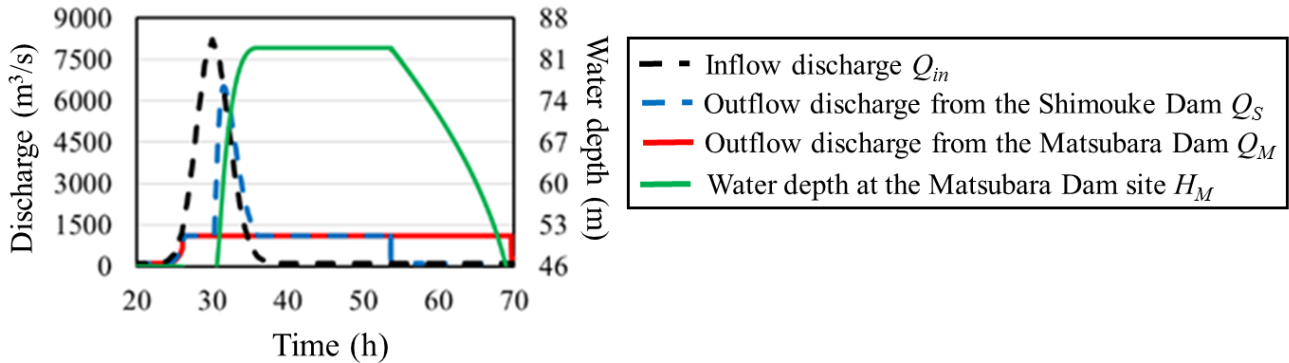
**Figure 2.** Flow discharges and water depths for the conventional flood control method (Case A1).

Based on the results of Case A1, a Cascade-type flood control method in which the design high water discharge for the upstream Shimouke Dam ( $Q_{a1}$ ) was equal to 1100 m<sup>3</sup>/s (the same as that for the downstream Matsubara Dam), was examined as Case A2. Figure 3 shows the inflow discharge  $Q_{in}$ , the discharge from the Shimouke Dam  $Q_S$ , the discharge from the Matsubara Dam  $Q_M$ , and the water depth upstream of the Matsubara Dam levee  $H_M$ , for the Cascade-type flood control method. In this figure,  $Q_{Mmax}$  is equal to 1100 m<sup>3</sup>/s (the same as  $Q_{a2}$ ), although the Shimouke Dam, which is located on the upstream side, overflows from its emergency spillway at around 31.2 h. The maximum water depth of 64.7 m upstream of the Matsubara Dam levee was 18.3 m lower than the levee height of 83.0 m, so there was still enough storage capacity in the dam. This result suggests that the Cascade-type flood-control capability in Case A2 was enhanced compared with the conventional flood control method used in Case A1. However, it is difficult to evaluate the capability of Cascade-type flood control quantitatively.



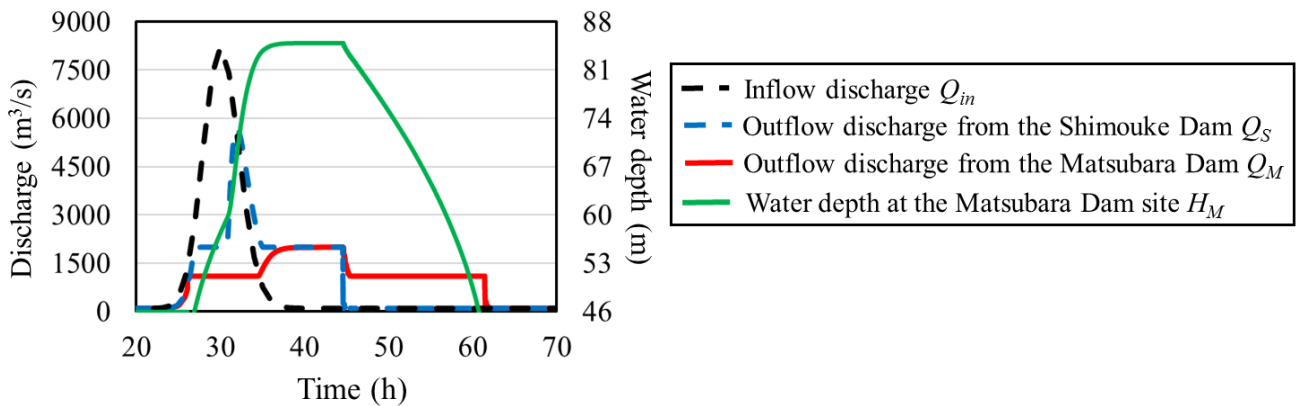
**Figure3.** Flow discharges and water depth for the Cascade-type flood control method (Case A2).

Then, to quantitatively evaluate the capability of the Cascade-type flood control,  $Q_p$  was increased to a limit so as not to overflow the Matsubara Dam, so that the dam's storage capacity was completely used; this is Cascade-type Case A3, shown in Figure 4. The maximum inflow discharge  $Q_p$  was 8227 m<sup>3</sup>/s, which corresponds to excessive flooding. The maximum value of  $H_M$  was 83 m (equal to the levee height of the Matsubara Dam). Therefore, it was found that the Cascade-type flood control method can control up to 30% larger floods compared with Case A1, where  $Q_p = 6339$  m<sup>3</sup>/s.



**Figure 4.** Flow discharges and water depth for the Cascade-type flood control method (Case A3).

Finally, a conventional flood control method, Case A4, was applied to the excessive flood in Case A3. Figure 5 shows hydrographs for the result of the conventional flood control in Case A4. As shown in the figure, the maximum water depth just upstream of the levee of the Matsubara Dam was 85 m, and the peak outflow discharge of  $Q_M$  exceeded 1100 m<sup>3</sup>/s (the value of  $Q_{a2}$ ), since Case A1 was the limit condition for the conventional flood control. This means that overflows occurred not only at the Shimouke Dam but also at the Matsubara Dam in spite of the conventional flood control used thus Case A4 was a failure.



**Figure 5.** Flow discharges and water depth for the conventional flood control method (Case A4).

#### 4 CASCADE-TYPE FLOOD CONTROL BY MULTIPLE DAMS COMBINED IN SERIES AND PARALLEL

In this section, which describes Cases B1-B4, the flood control capability of the Cascade method in a situation where dams are combined in series and in parallel by installing a new dam was examined. A virtual dam was set up on the Chikugo River, as shown in Figure 1. For simplicity, the storage capacity and the flood control capacity of the virtual dam was set to be the same as the flood control capacity of the Shimouke Dam in order to evaluate only the flood control effect. The flood inflow points in Cases B1-B4 are Tsuetate on the Chikugo River, Tochino on the Tsue River, and Kaminoda on the Kaminoda River.

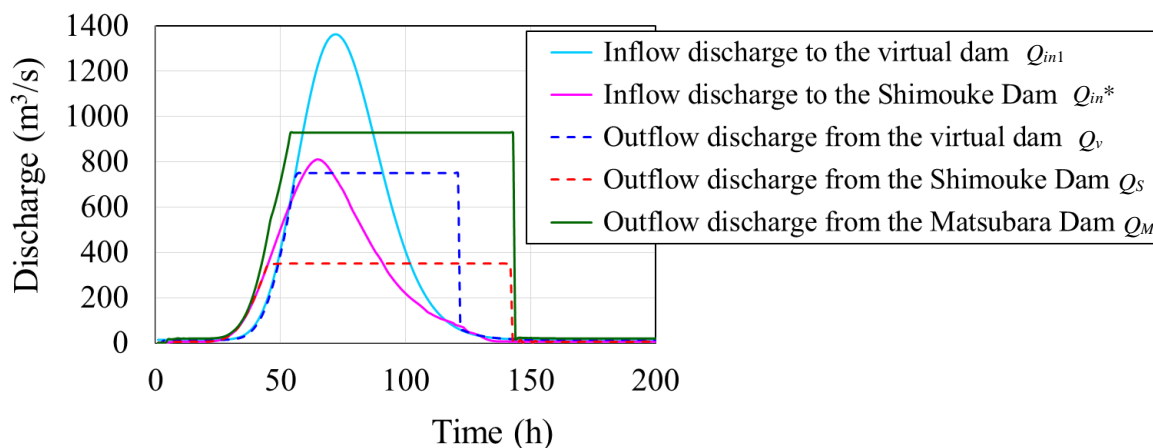
Equation [2], which is isomorphic to Eq. [1], is used for each upstream end as the boundary condition for inflow discharge  $Q_{inj}$ :

$$Q_{inj}(t) = Q_{bj} + (Q_{pj} - Q_{bj}) \left\{ \frac{t}{t_{pj}} \exp \left( 1 - \frac{t}{t_{pj}} \right) \right\}^{c_j}, \quad [2]$$

where  $t_{pj}$  is the peak time of each flood,  $Q_{bj}$  is the ordinary water discharge,  $c_j$  is a constant related to the shape of the hydrograph,  $t$  is time, and the subscript “ $j$ ” indicates the position of the inflow ends;  $j = 1$  (Tsuetate),  $j = 2$  (Tochino), and  $j = 3$  (Kaminoda). In Cases B1-B4,  $t_{p1} = 71$  hr,  $t_{p2} = 72$  hr,  $t_{p3} = 54$  hr,  $Q_{b1} = 13.9$  m<sup>3</sup>/s,  $Q_{b2} = 3.0$  m<sup>3</sup>/s,  $Q_{b3} = 2.6$  m<sup>3</sup>/s,  $c_1 = 20$ ,  $c_2 = 25$ , and  $c_3 = 15$ , referring to conditions from a past flood.

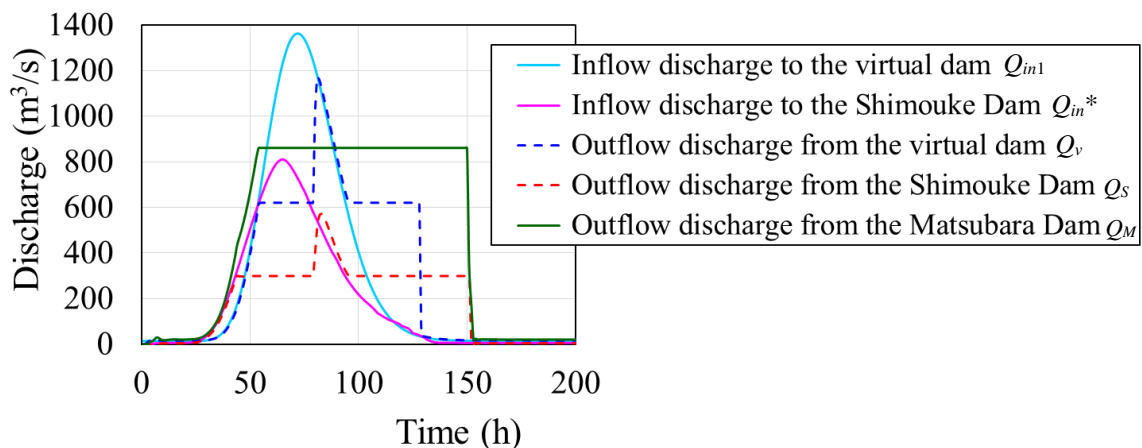
First, for the conventional flood control method of Case B1, the maximum inflow discharge  $Q_{pj}$  and design high water discharge  $Q_{ai}$  corresponding to harmless discharge were determined for the following conditions. The subscript “ $i$ ” (=1 to 3) indicates each of the three dams—with “1” denoting the virtual dam, “2” the Shimouke Dam, and “3” the Matsubara Dam. The actual flood control capacity of the existing dams is 51.3 million m<sup>3</sup> for the Shimouke Dam and 45.8 million m<sup>3</sup> for the Matsubara Dam. This supposes that  $Q_{a2}$  equals 350 m<sup>3</sup>/s and  $Q_{a1}$  equals 750 m<sup>3</sup>/s, the latter of which is the actual design high water discharge of the Matsubara Dam (1100 m<sup>3</sup>/s) minus  $Q_{a2}$  (350 m<sup>3</sup>/s). For the peak inflow discharges of the tributaries, a  $Q_{p2}$  value of 570 m<sup>3</sup>/s and a  $Q_{p3}$  value of 443 m<sup>3</sup>/s were adopted as the limit values for which the Shimouke Dam can control the flood with  $Q_{a2} = 350$  m<sup>3</sup>/s without using the emergency spillway. A  $Q_{p1}$  value of 1363 m<sup>3</sup>/s was obtained as the maximum value for which the virtual dam can control the flood with  $Q_{a1} = 750$  m<sup>3</sup>/s. Finally, a  $Q_{a3}$  value of 929 m<sup>3</sup>/s was calculated as the limit for which the Matsubara Dam can control the inflow floods without overflowing.

Figure 6 shows discharge hydrographs at several important positions for the conventional flood control method in Case B1: the inflow discharge to the virtual dam  $Q_{in1}$ ; the inflow discharge to the Shimouke Dam  $Q_{in}^*$ , which is the flow discharge at the village of Kawahara after the Kaminoda River joins the Tsue River; and outflow discharges from each dam (see Figure 1). Figure 6 shows that appropriate conventional flood control was performed in Case B1 given that each dam had maximum outflow discharges that were the same as each design high water discharge without overflowing. As a matter of course, the maximum discharge from the Matsubara Dam  $Q_{Mmax}$ , which was used to evaluate the flood control effect, was 929 m<sup>3</sup>/s (the same as  $Q_{a3}$ ).



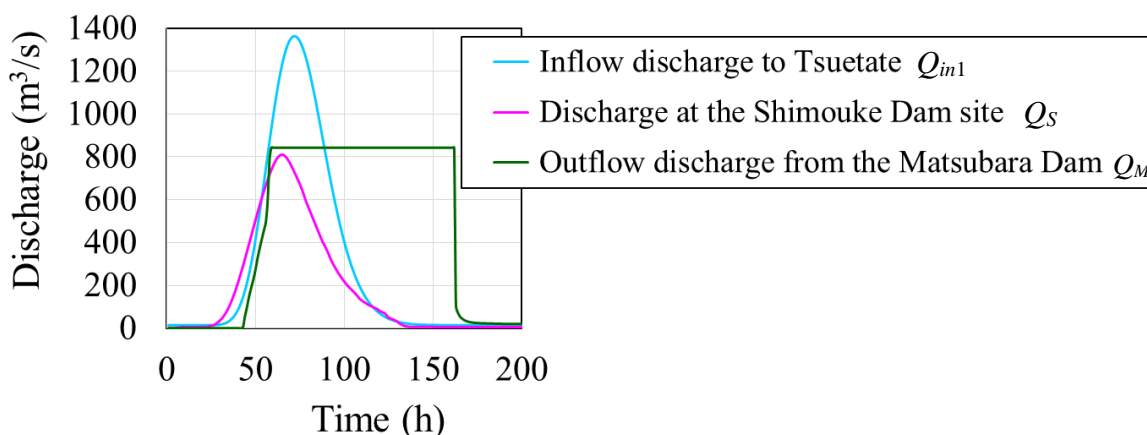
**Figure 6.** Flow discharges in the conventional flood control method (Case B1).

Next, based on the result of Case B1, a Cascade-type flood control method, Case B2, was performed, which combined dams in series and parallel. The minimum value of  $Q_{a3}$  without overflow at the Matsubara Dam was determined by trial and error, with the conditions that  $Q_{a1}$  and  $Q_{a2}$  were reduced, and overflows from the emergency spillways of the Shimouke Dam and the virtual dam were permitted. Figure 7 shows the results of inflow and outflow discharge for Case B2. In case B2,  $Q_{Mmax}$  was 861 m<sup>3</sup>/s (the same as  $Q_{a3}$ ), which is 7.3% smaller than the  $Q_{Mmax}$  in Case B1 (929 m<sup>3</sup>/s), although overflow occurs in the two upstream dams in Case B2. Therefore, it was found that the flood control capability of the Cascade-type method with dams combined in series and in parallel was significantly enhanced.



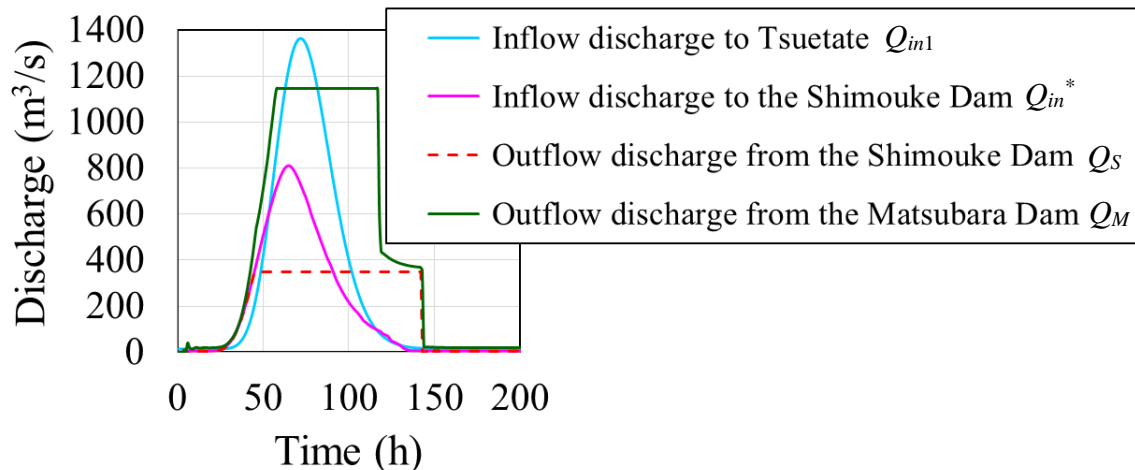
**Figure 7.** Flow discharges in the Cascade-type flood control method (Case B2).

Case B3 examined conventional flood control using only the Matsubara Dam (i.e., without the levee bodies of the Shimouke Dam and virtual dam), whose flood-control capacity was set at 148.4 million  $m^3$  by raising its levee body to match the total flood-control capacity of the three dams in Cases B1 and B2. Figure 8 shows the results of Case B3, where  $Q_{a3} = 843 \text{ m}^3/\text{s}$  as the minimum limit for which the Matsubara Dam never overflows. In Figure 8, appropriate flood control is demonstrated since  $Q_{Mmax}$  is  $843 \text{ m}^3/\text{s}$  (the same as  $Q_{a3}$ ), and the peak discharge from the Matsubara Dam in Case B3 was 9.3% smaller than that in Case B1. Additionally, the  $Q_{Mmax}$  of  $843 \text{ m}^3/\text{s}$  in Case B3 is almost equal to that in the Cascade-type flood control method of Case B2 ( $861 \text{ m}^3/\text{s}$ ), which means that the Cascade-type method becomes linear even when dams are combined in series and in parallel, as found for the series condition by Oshikawa and Komatsu (2015).



**Figure 8.** Flow discharges in the conventional flood control method using a large dam (Case B3).

Finally, we examined a conventional flood control case, Case B4, using the two existing dams without the virtual dam, that is, the actual situation, in order to estimate how large the flood in Case B1 is in this hypothetical scenario. Figure 9 shows the results of Case B4, where  $Q_{a2}$  and  $Q_{a3}$  were minimized, without overflow from the emergency spillways of the Shimouke and Matsubara Dams. The  $Q_{Mmax}$  in Case B4 is  $1146 \text{ m}^3/\text{s}$ , which is 23% larger than the  $Q_{Mmax}$  of  $929 \text{ m}^3/\text{s}$  in Case B1. This means that Case B1 roughly corresponds to the flood adaptation measure for a flood 20% larger than the current flood control plan with the construction of the virtual dam in the Chikugo River. Cases B2 and B3 were subsequently compared with Case B1 as the standard.



**Figure 9.** Flow discharges in the present situation using two existing dams (the Shimouke and Matsubara dams) (Case B4).

## 5 CONCLUSIONS

This study demonstrated that Cascade-type flood control is much more effective than conventional flood control. In the upper reaches of the Chikugo River, the flood control capability of the downstream side, which is generally more important than that of the upstream side, was significantly enhanced by allowing overflows from the emergency spillway. Additionally, even when multiple dams are combined in series and in parallel, Cascade-type flood control was remarkably effective.

Cascade-type flood control corresponds to a positive use of a so-called “provisory operation”, which is an originally pessimistic slide-gate operation of each dam at the time of a serious flood beyond a designed flood (Oshikawa et al., 2008). Since the Cascade method can strengthen flood control capability merely by altering the gate operation of existing dams, the method will be extremely useful in responding to an increased frequency and severity of disaster hazards due to global warming.

## ACKNOWLEDGEMENTS

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