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Cascade Type Flood Control Using Plural Dams

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ABSTRACT:
A new concept for flood control called ‘Cascade’ method which permits dams to overflow around an upstream region with a sequence of dams set in a river is proposed. Plural small scale dry dams should be constructed in series instead of a large scale dam in order to prevent flood disaster and preserve the natural environment. Recently a flood control dam without a slide gate in spillway, known as ‘dry dam’, has been reviewed, planned and built in some sites in Japan. Under a condition of a common reservoir capacity, the Cascade type flood control permitting upstream dams to overflow except for the most downstream dam in a river was compared with a conventional one not to overflow each dam. As a result, it was made clear that the Cascade type using plural dry dams is more effective than the conventional one. In addition, the Cascade type flood control permitting upstream dams to overflow from emergency spillways can be applied to normal storage dams with slide gates. Therefore, it could become an effective adaptation method for the global warming problem since it is performed by only changing how to operate slide gates in existing storage dams set in series.

Keywords: Cascade type flood control, plural dams set in series, overflow, dry dam, adaptation method

1. INTRODUCTION

In recent years, we have observed an increase in disaster hazards such as intensified fierce rains, droughts and typhoons, presumably caused by the global warming [IPCC (2007)]. Hereafter, various harmful effects of the global warming would be revealed, and an unexperienced catastrophic disaster due to an extremely large-scale flood exceeding a design level makes us worried. Measures against flood disasters should be taken to prevent such kind of catastrophic disasters [Science Council of Japan (2008)].

In addition, natural environment preservation has been respected after the rapid economic high growth in Japan. We have to treat with increasing disaster hazards and natural environment preservation based on requirements of society at the same time. Moreover, it is extremely difficult to implement large-scale public works especially in Japan as budgets of public works projects have been reduced because of the long-term economic slump. Therefore, small-scale public works (e.g. small dam constructions) would be considered in the future.

Plural small scale dry dams around a river basin should be constructed instead of a large scale dam hereafter in order to prevent flood disasters and preserve natural environment especially in Japan. Recently, a flood control dam without a slide gate in spillway, known as ‘dry dam’, has been reviewed, planned and built in some sites in Japan [Sumi (2008), Oshikawa *et al*. (2008), Kantoush and Sumi (2010)]. Until 1970’s, relatively small dry dams had been constructed in order to prevent agricultural disasters in Japan. Since examples of utilized full-scale dry dam to protect human lives and property are very small in Japan, e.g. Masudagawa dam, further research for such kind of dry dams is needed. On the other hand, there are some good examples in USA from 1920’s such as dry dams at Miami Conservancy District in Ohio [Sumi (2008), Kantoush and Sumi (2010)]. In addition, quite a lot of dry dams, called as “flood retention basin” or “flood control basin”, are found in Austria which are almost eco-friendly small scale earth fill dams [Sumi (2009)].

We suggest a new flood control concept called ‘Cascade’ method which permits dams to overflow around an upper reach region with plural dams set in series in a river. In this study, flood control capability of plural dry dams based on the new concept is investigated using a numerical simulation. It is expected that the new flood control method permitting upstream dams to overflow from emergency spillways except for the most downstream dam is to strengthen flood control capability in a lower reach region which is generally more important than that in an upper reach one.

In addition, the new Cascade method will be measures for excessive floods. The new method permitting upstream dams except for the most downstream dam to overflow from emergency spillways is applied to normal storage dams with slide gates. If it is useful, flood control capability of existing storage dams constructed in series could be easily increased by only changing a conventional gate operating method.

2. OUTLINE OF THE SIMULATION AND ITS CONDITIONS

In this study, suppose that distances between dams set in series in a river are small, and there is no branch river and no direct inflow of precipitation. Thus, only inflow from upper reaches to dams is important in the river. In this study, an overflow from emergency spillways on the top of each dam body often occurs. This study assumes that dry dams are constructed in an upstream area where overflows from dams and increases of water level around the river are permissible to a certain degree, which is a non-residential area, a wasteland or a farmland. In other words, all area upstream from the final dam which is the one constructed at the most downstream site is considered as a kind of retarding basin. Therefore, in the Cascade method, overflow from an emergency spillway on the only final dam must be avoided.

The basic equation is an integrated continuity equation as follows:

$$V_i(t)=\int_0^t \left(Q_{in_i}-Q_{out_i}\right)dt \qquad (1)$$

where i is a dam number from an upstream side and a natural number, t is time, $V_i(t)$ is stored water volume in ith dam where $V_i(t=0)=0$, Q_{ini} is the inflow discharge to an ith dam, Q_{outi} is its outflow discharge. Since there is no branch river in this study, Q_{outi} agrees strictly with Q_{ini+1} ($Q_{outi}=Q_{ini+1}$). Because a cross section of a hole which is an orifice opened in the bottom center of a dam body for flood control must be small, an outflow discharge from the hole is assumed to be decided by a simultaneous water surface level in a dam reservoir with the Torricelli theorem. An outflow discharge from an emergency spillway on the top of the dam body in an overflowing situation is estimated by an overflow formula that overflow discharge is proportional to overflow depth to the 3/2 power [JSCE (1999)]. Total outflow discharge from each dry dam is calculated by summing the outflow discharge from the bottom hole and the overflow discharge from its emergency spillway. In this study, sedimentation storage capacity is discounted in each dam for easiness.

The flood hydrograph $Q_{in}(t)$ [$=Q_{in1}(t)$] which is an inflow discharge for a most upstream dam as a boundary condition is given by the following equation [JSCE (2002)]:

$$Q_{in}(t)=Q_b+(Q_p-Q_b)\left\{\frac{t}{t_p}\exp\left(1-\frac{t}{t_p}\right)\right\}^c \qquad (2)$$

where Q_p is the peak flow discharge, Q_b is the normal flow discharge, t_p is the arrival time of Q_p, and c is a constant coefficient.

The cross sectional shape of a dam body is a quadratic function with a height of dam H and a length of top of dam L (see Fig. 1). H is defined as the vertical length from the bottom to the crest height of a dam. Relationship between L and H is $L=H*200/90$ where L is 200(m) in the case of H=90(m). In this study, the width of an emergency spillway B is the same as L for easiness ($B=L$). In addition, the height of an emergency spillway k is assumed to be long enough vertically. The slope of a reservoir bed and the river one are 0.01 (=tanθ). A sectional area of the bottom hole for flood control is designed to make the design high water discharge Q_a flow in the situation where each water level in a dam reservoir is equal to H.

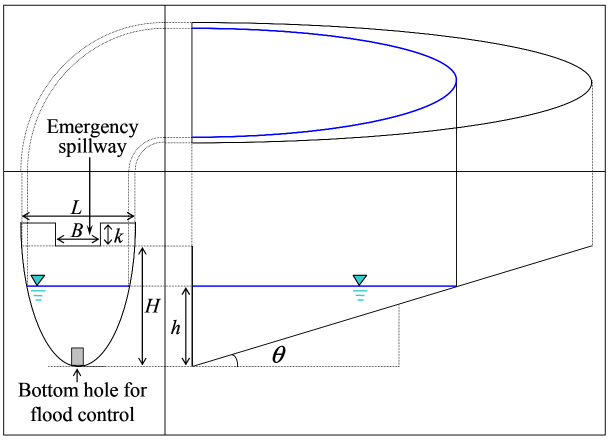

Figure 1. Dam shape and definition of symbols used

In this study, relatively large dams whose heights are about 100(m) are used because of the easiness of comparison between the Cascade type flood control method and a conventional one. In fact, in Japan, the authors consider that relatively small dams should be constructed in the future in order to preserve the natural environment as mentioned before.

3. FLOOD CONTROL CAPABILITY OF DRY DAMS SET IN SERIES

An outflow discharge in the Cascade-type flood control method was compared with that in a conventional one in a river where plural dry dams were constructed (Case1s). In this chapter, computational conditions except for Q_p in Case1-5 were as follows: Q_p=8887(m^3/s), Q_b=219(m^3/s), t_p=20(hr), c=20, H=100(m).

3.1. Cases in Three Dry Dams Set in Series

Three dry dams were constructed in a river in series. Based on the conventional flood control method without an overflow, appropriate design high water discharges Q_a were found to be 6773(m^3/s), 5646(m^3/s), 4792(m^3/s) from the most upstream dam by trial and error (Case1-1). Figures 2 and 3 show the time series of inflow discharge for the upstream dam and the outflow discharges from the three dams in Case1-1, and those of the inflow discharge and water surface level in each dam reservoir in the case, respectively. The maximum outflow discharge in each dam in Fig. 2 is 6773(m^3/s), 5646(m^3/s), 4792(m^3/s) from the upstream which are equal to each Q_a, because each water surface level in Fig. 3 is the same as H(=100(m)) in the exact times of each maximum outflow discharge.

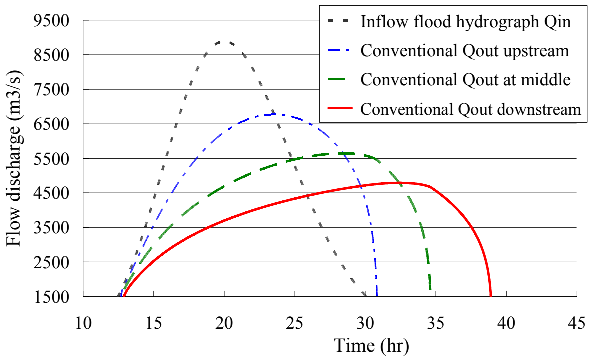

Figure 2. Flow discharges in the conventional type (Case1-1)

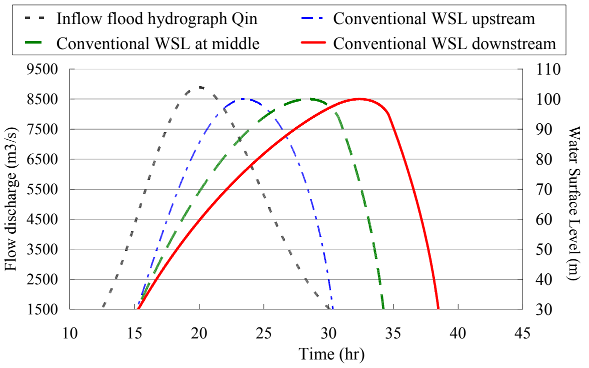

Figure 3. Inflow discharge and water surface levels in the conventional type (Case1-1)

The Cascade method which permits overflows from emergency spillways in the upstream dam and the middle one was applied as Case1-2. From the result of Case1-1, this river in the Cascade method can flow up to 4792(m^3/s) which is equivalent to Q_a in the downstream dam. Therefore, common Q_a [=4792(m^3/s)] was used for the three dams in Case1-2 as the Cascade method for easiness. The time series of the inflow discharge for the upstream dam and the outflow discharge from each dam in Case1-2, and those of the same inflow discharge and water surface level in each dam reservoir in the case are depicted in Fig. 4 and in Fig. 5, respectively. In Fig. 4, the maximum outflow discharge in the downstream dam is 4540(m^3/s) which is 5.3% smaller than Q_a, which means flood control capability of the Cascade-type is higher than that of the conventional one although the flood overflows the upstream and middle dams from each emergency spillway. In addition, there is some unoccupied space in storage capacity on the downstream dam even at the time of the maximum outflow discharge in Case1-2 because the water surface level in the dam in Fig. 5 has a maximum value at the time, and it is 89.7(m) which is smaller than H(=100(m)).

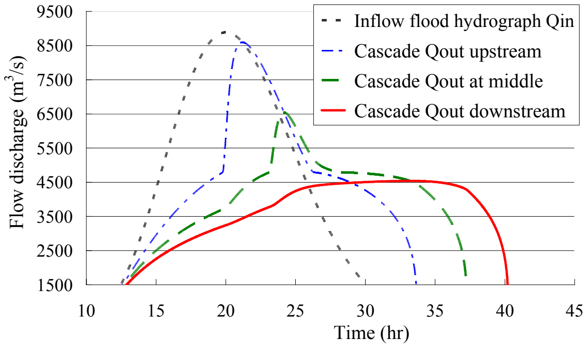

Figure 4. Flow discharges in the Cascade type (Case1-2)

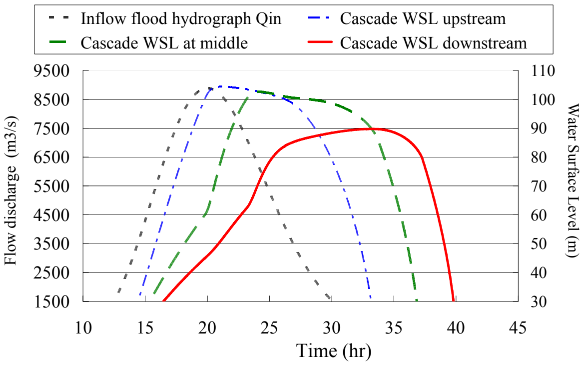

Figure 5. Inflow discharge and water surface levels in the Cascade type (Case1-2)

The Cascade method is very useful as a flood control one. In consideration for the unoccupied space in Case1-2, the optimum common Q_a in the three dams which was the critical value in the case without overflow at the downstream dam was found to be 4000(m^3/s) for Case1-3 in the Cascade method by trial and error. Figures 6 and 7 demonstrate the time series of the inflow discharge for the upstream dam and the outflow discharge from each dam in Case1-3, and those of the same inflow discharge and the water surface level in each dam reservoir in the case, respectively. The maximum water surface level in the downstream dam in Fig. 7 is 100(m) which is the same as H, when the outflow discharge from it is maximum, 4000(m^3/s), at t=29.2(hr) in Fig. 6. The Cascade type flood control is remarkably effective because the value of discharge, 4000(m^3/s), in Case1-3 is 17% smaller than the corresponding value in Case1-1, 4792(m^3/s). This is the reason why overflows at the upstream and middle dams suddenly increase each inflow discharge when the water level in following each reservoir is still not so high. From the viewgraphs, that is understood for the upstream dam at t=19.1(hr) both from Cascade Q_{out} upstream in Fig. 6 and from Cascade WSL at middle in Fig. 7, and for the middle dam at t=22.0(hr) both from Cascade Q_{out} at middle in Fig. 6 and from Cascade WSL downstream in Fig. 7.

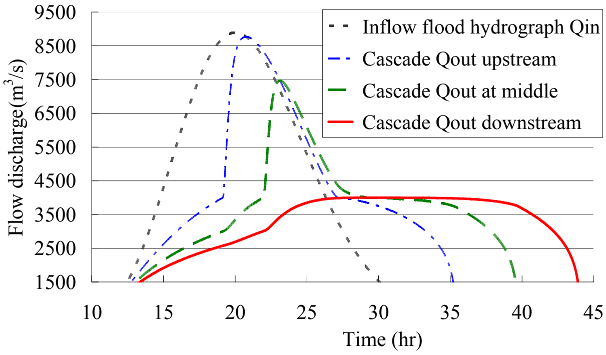

Figure 6. Flow discharges in the Cascade type (Case1-3)

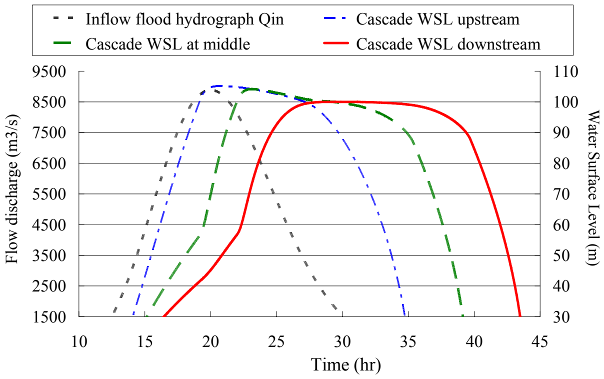

Figure 7. Inflow discharge and water surface levels in the Cascade type (Case1-3)

The Cascade-type flood control is significantly more effective than the conventional one even if maximum water volume impounded in a Cascade-type flood control dam perfectly accords with that in a conventional one in consideration for an eventual increment of storage capacity owing to overflow depth. Since overflow depths in the upstream and middle dams in the Cascade type flood control were disregarded in comparison with outflow discharges in Case1-1 and those in Case1-3, it is possible to overestimate superiority of the Cascade type to a certain degree. Thus, in Case1-4, each height of the conventional dams in Case1-1 (H=100(m)) was raised to the same height of each maximum water surface level in Case1-3, so that water storage capacity in conventional dams in Case1-4 was perfectly equal to each maximum water storage volume in the Cascade-type dams in Case1-3. Height of dams in Case1-4 was 105.1(m), 104.2(m) and 100.0(m) from the upstream (see Fig. 7).
Figures 8 and 9 illustrate the time series of the inflow discharge for the most upstream dam and the outflow discharges from the three dams in Case1-4, and those of the inflow discharge and the water surface level in each dam reservoir in the case, respectively. We can recognize that the maximum water surface level in each dam in Fig. 9 agrees with those in Fig. 7. Maximum outflow discharges in Fig. 8 are 6507(m^3/s), 5310(m^3/s), 4510(m^3/s) from the upstream which are equal to each Q_a since the times at maximum outflow discharges in Fig. 8 are consistent with those at maximum water surface levels in Fig. 9. The maximum outflow discharge in the Cascade-type downstream dam in Case1-3, 4000(m^3/s), is 11% smaller than that in the conventional one in Case1-4, 4510(m^3/s). Practically increment of water storage capacity due to overflow depth is allowable to a certain degree. Therefore, the Cascade-type flood control has about 11 to 17% predominance compared with the conventional one in this condition.

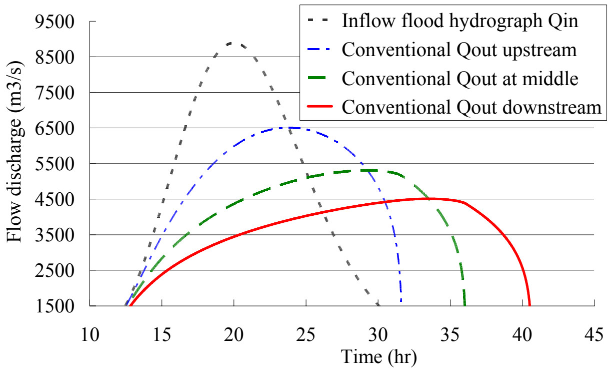

Figure 8. Flow discharges in the conventional type (Case1-4)

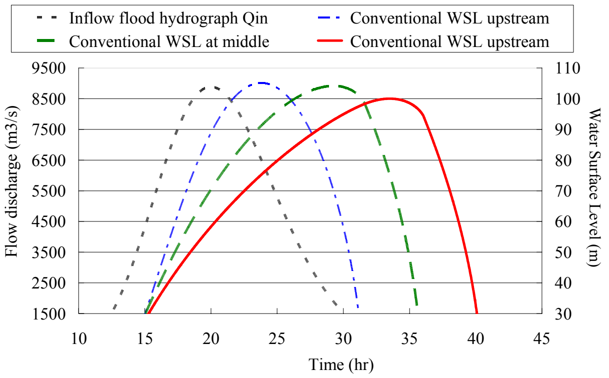

Figure 9. Inflow discharge and water surface levels in the conventional type (Case1-4)

The Cascade-type flood control is also applicable as a measure against excessive flood. In the Cascade method, the peak inflow discharge, Q_p in Eq. 2, can be increased up to 9717(m^3/s) in the condition where the others are the same as Case1-2 because there was an unoccupied space even at a maximum water surface level in dam reservoirs in Case1-2. As Case1-5 in the Cascade-type flood control, Fig. 10 shows the time series of inflow discharge for the upstream dam in the case where the outflow discharge from the downstream dam had a peak when its storage capacity was completely filled with water. In addition, Fig. 10 includes the time series of outflow discharge from each three dams in the case. Though the maximum outflow discharge from the downstream dam in Case1-5, 4792(m^3/s), is equal to that in Case1-1, Q_p (=9717(m^3/s)) in Case1-5 is 10% larger than Q_p (=8887(m^3/s)) in Case1-1. Therefore, the Cascade method will control flood exceeding a design level in the range where $Q_p \leq 9717$(m^3/s). The Cascade method could be one of the adaptation methods for global warming problem.

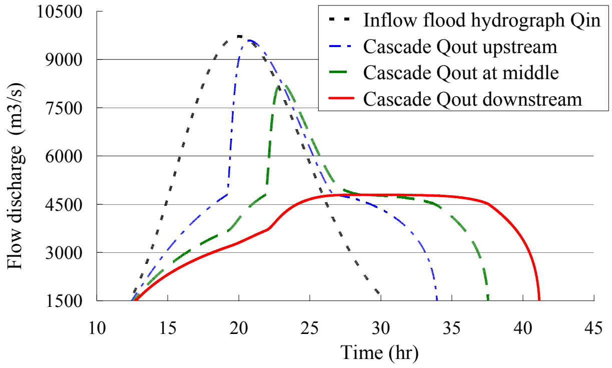

Figure 10. Flow discharges in the Cascade type (Case1-5)

3.2. Effect of the Number of Dry Dams Set in Series

Efficiency of the Cascade-type flood control becomes larger as the number of a sequence of dams increases. In the cases where the number of dry dams set in series, *N*, was 1, 2, 3, 4 and 5, the Cascade type flood control were compared with the conventional one like the comparison between Case1-1 and Case1-3. Computational conditions in this section were the same as those in the former section except for dam number. Fig. 11 gives the relationship between *N* and Q_{Nmax}/Q_p, where Q_{Nmax} is the maximum outflow discharge from the most downstream dam in each case. Results of the two cases where *N*=3 are completely the same as the result of Case1-1 in the conventional method and that of Case1-3 in the Cascade one. The differences between Q_{Nmax}/Q_p in the conventional flood control and that in the Cascade one increases with *N* in Fig. 11. Therefore, the Cascade-type flood control is more useful in the cases where the number of dams is larger.

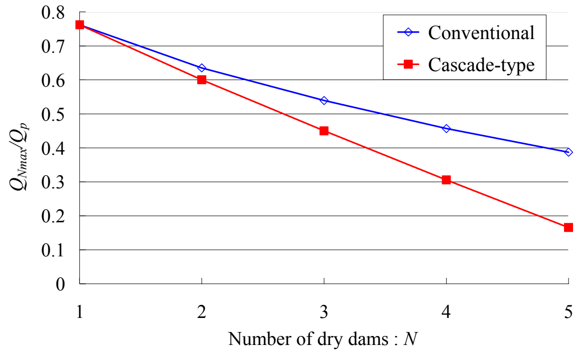

Figure 11. Relationship between *N* and Q_{Nmax}/Q_p

4. CASCADE TYPE FLOOD CONTROL FOR WATER STORAGE DAMS WITH SLIDE GATES

The Cascade-type flood control is applicable not only for dry dams constructed in series but also normal water storage dams with slide gates. In a normal water storage dam, so-called "provisory operation" which is the pessimistic gate operation at the time of flood beyond design flood discharge is prescribed [Oshikawa *et al.* (2008)]. Therefore, the application of the Cascade-type flood control for normal water storage dams is analogous to the positive "provisory operation" except for a downstream dam in the case where there is no riverside resident around upper reach region from the dam.

4.1. Computational Methods

A river with 4 dams set in series in which one was a normal water storage dam with a slide gate most upstream and the others were dry dams downstream was discussed. Heights of dams were all 100.5(m). Outflow discharges controlled artificially at the normal storage dam with the gate flowed into the following three dry dams in turns, and the outflow discharges at the most downstream dry dam were compared under some gate operating conditions. In provisory operation, rapid water level rise is usually avoided for safety by a preparatory gate operation to a certain degree. However, in this study as an extreme case, the outflow discharge from the normal dam agrees with its inflow discharge as soon as the overflow happens for easiness. Thus, an overflow formula to estimate the outflow discharge from an emergency spillway of the normal dam was never used, while the same formula as Case1s was adopted for the other dry dams.

Time series of outflow discharge from the upstream normal dam with a slide gate was calculated under the following conditions. In Case2s (Case2-1, Case2-2, Case2-3), the design flood into the upstream dam was Q_p=8000(m^3/s), Q_b=150(m^3/s), t_p=20(hr) and c=20 in Eq. 2. In Case2s with an ideal virtual gate operation, the time series of outflow discharges agreed with those of its inflow discharge until the inflow discharge reached to each Q_a. In Case2-1 with an ideal virtual gate operation, the moment the inflow discharge increased up to Q_a (=5000(m^3/s)), water storage started and the gate kept its outflow discharge at 5000(m^3/s) for a while. After the inflow hydrograph taking peak, the dam reservoir upstream was filled with water and its inflow discharge became 5000(m^3/s) at the same time. After keeping outflow discharge at the uniform 5000(m^3/s) with the gate in order to lower water level in the dam reservoir upstream, as soon as the storage capacity available was zero, the gate adjusted outflow discharge to its inflow discharge. Therefore, maximum outflow discharge in Case2-1 was 5000(m^3/s) same as Q_a, and perfect flood control was performed in the upstream dam under a conventional flood control concept. On the other hand, Case2-2 and Case2-3 were different from Case2-1 only on Q_a which equalled to 3000(m^3/s) in Case2-2 and 4000(m^3/s) in Case2-3. Since Case2-1 was the critical condition without overflowing in the upstream dam with the slide gate, Case2-2 and Case2-3 were conditions with overflowing in the upstream dam, and those two cases corresponded to the Cascade type flood control. Q_a in other dry dams downstream was 3000(m^3/s) same as Q_a for the upstream dam in Case2-2. Fig. 12 gives the time series of the inflow discharge into the upstream dam and the outflow discharges from it in each case. We can recognize that the overflowing causes discontinuous rapid increasing in Case2-2 and Case2-3 and subsequent each outflow discharge is the same as its inflow discharge while each inflow discharge is larger than each Q_a.

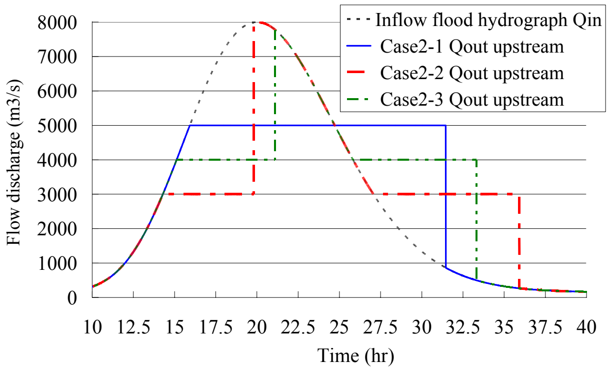

Figure 12. Inflow and outflow discharges for the upstream dam with a slide gate in Case2

4.2. Results and Discussions on Case2

For storage dams with slide gates, the Cascade type flood control is useful to reduce the outflow discharge from a downstream dam. Fig. 13 shows the time series of the inflow discharge into the upstream dam with gates and the outflow discharge from the most downstream dry dam in each case. All maximum outflow discharges from the downstream dam are smaller than 3000(m^3/s) which is design high water discharge in all case. Thus, all the flood control is appropriate. However, maximum outflow discharge is different in each case, and that in Case2-1 is the worst 2960(m^3/s), that in Case2-2 is the best 2747(m^3/s), and that in Case2-3 is moderate 2875(m^3/s). Therefore, as the rapid increase of outflow discharge due to overflowing from the upstream dam reduces the maximum outflow discharges from the downstream dam, conventional "provisory operation" for water storage dams with slide gates should be reviewed and changed to the Cascade-type dam operation.

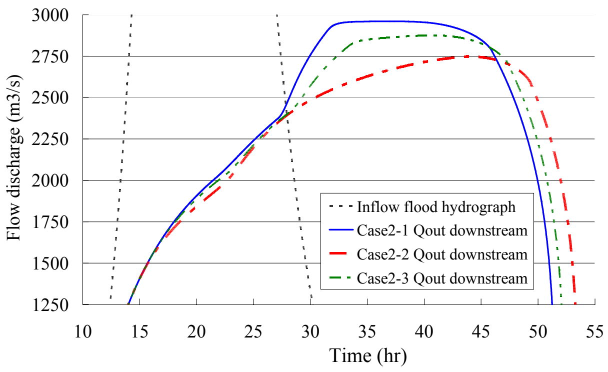

Figure 13. Inflow and outflow discharges for the most downstream dry dam in Case2

5. CONCLUTIONS

The new "Cascade-type" flood control concept is much more effective than the conventional one which can not permit overflowing from each dam. The new concept allows overflowing from upstream dams set in series except for the most downstream dam which is generally the nearest dam from residential area. In this study, a river basin with a sequence of dry dams was mainly discussed using a numerical simulation, and the advantage of the Cascade type flood control was demonstrated. In addition, the Cascade type flood control is also applicable to gate operations of water storage dam, which is positive use of the "provisory operation", which is originally a pessimistic gate operation at the time of flood beyond a design high water discharge. Therefore, it should become an effective adaptation method for the global warming problem since the new method is performed by only changing how to operate slide gates in existing storage dams constructed in series. Moreover, the criticism that overflowing from a downstream dam would cause severe flood damage around residential area though water storage capacity in upstream dams had enough room can be avoided in the Cascade method because it controls flood with using each full storage capacity from the most upstream dam in turn.

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