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Study on rational control model for excess flood by utilizing rainfall prediction

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ABSTRACT: The construction of new flood control facilities has been slow due to various constraints despite a steady increase of the phenomenon of extreme precipitation associated with climate change. With this status, the more efficient and effective operation of existing dams are essential. This study examined the applicability of a rational method for flood control, including excess flood, while utilizing rainfall prediction by the weather research and forecasting model (WRF), the accuracy of which has significantly improved in recent years. The study also examined a range of ideas for more effective flood control operation, including the handling of errors of rainfall prediction by the WRF model, risk management with due consideration of flood control and water use and the effect of the remodelling of spillways.

1 INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007) points out the strong likelihood of the continual occurrence of heavy precipitation events as an outcome of climate change. It is now imperative for the world to come up with suitable measures to deal with such likelihood. In Japan, the number of dams newly constructed by the Ministry of Land, Infrastructure, Transport and Tourism has been declining since the peak year of 1993 while the number of dams managed by the Ministry has increased to 532. Under these circumstances, it is requested that the functions of existing dams should be further strengthened.

In this study, rainfall prediction was conducted using the WRF model which has significantly improved recently in terms of accuracy to the extent that the model now offers highly reliable rainfall prediction for up to 48 hours (Toyoda, 2009). This exercise was followed by the simple calculation of the lost amount of rainfall in a basin to establish the total volume of inflow to a dam for the purpose of examining an efficient flood control method utilizing the dam capacity to the maximum. The applicability of this method was then examined with actual flood events, including those of excess floods. The purpose of this exercise was to establish integral operation utilizing the capacity for water use and the flood control capacity of a dam for efficient flood control through preliminary discharge operation in tandem with operation to supply water for productive use and utilization of the total dam capacity. The ultimate aim was to minimize flood damage downstream.

2 FLOOD CONTROL METHOD UTILIZING RAINFALL PREDICTION BY WRF METHOD

In the study, the volume of inflow to a dam was predicted based on rainfall prediction by the WRF model and the reduction of the maximum discharge rate below the discharge rate stipulated in the dam operation rules for the purpose of establishing a more effective flood control method. This simulation was conducted for 12 existing dams in Japan.

Figure 1 is a flow diagram of the flood control method examined by the study. In consideration of the duration of design rainfall, the rainfall for the next 48 hours was predicted using the WRF model.

This method using rainfall prediction data can be expected not only to improve the positive effects of flood control but also carry risks because of errors in prediction. To determine the impacts of rainfall prediction errors on such risks for dam management as an insufficient flood control capacity and unfulfilled water use capacity, an error range where the actual rainfall level is either above or below the predicted level was set in addition to the rainfall prediction value by the WRF model. Given the fact that the rainfall prediction errors of the WRF model were not clearly established, in this study the error rates for 48 hour accumulative rainfall were based on the study by the Japan Meteorological Agency (Wada, 2006). The predicted rainfall range was estimated by multiplying the predicted rainfall calculated by the WRF model, by the error rate defined as the ratio between the predicted rainfall and the actual one where the maximum and the minimum values are 1.43 and 0.714 respectively. In this study, it was presumed that the actual rainfall level fell within this predicted rainfall range as the first step to analyze the impacts of ranged rainfall prediction on flood control operation. The rainfall prediction value was renewed every six hours in accordance with the acquisition of initial condition data for calculation by the WRF model. Flood control simulation was conducted to determine the hourly dam operation shown in Figure 1 according to the level of inflow every hour.

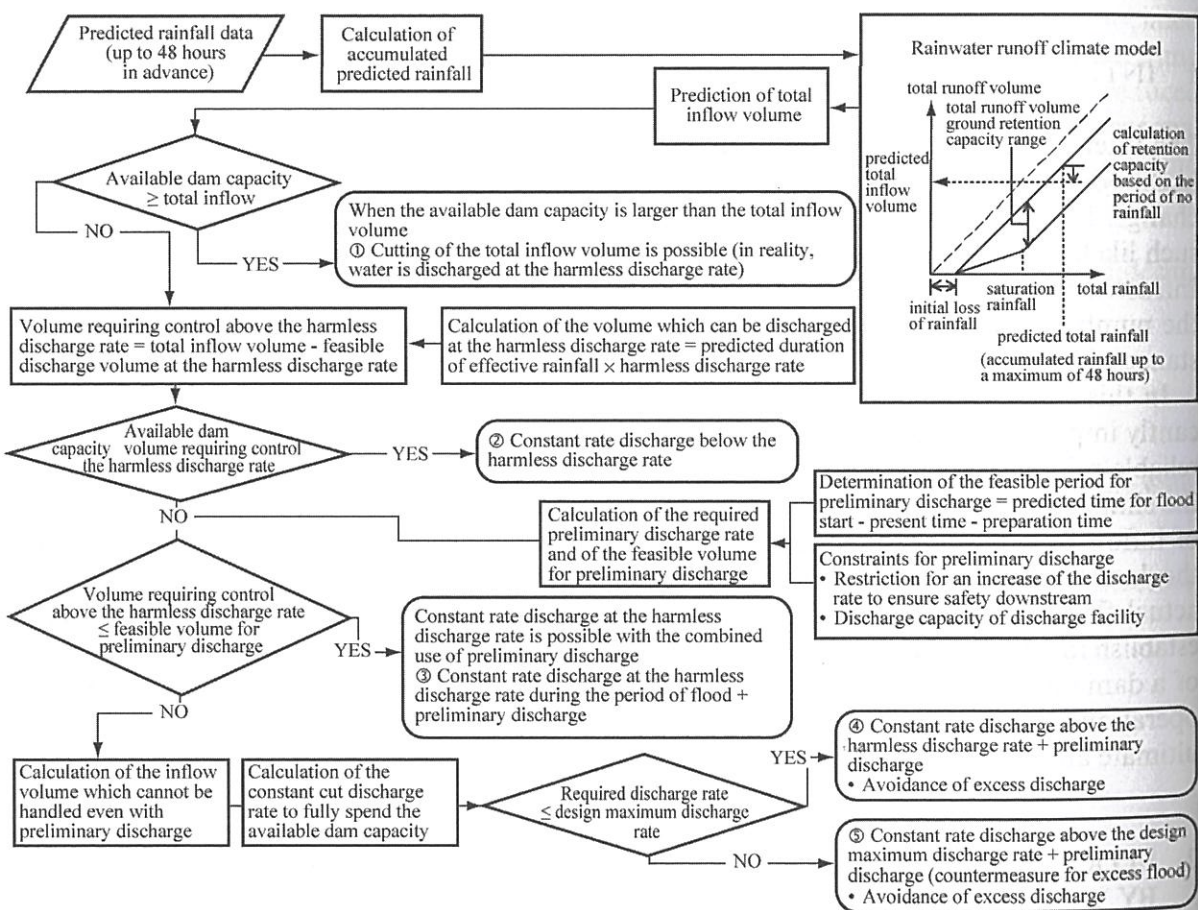


Figure 1. Flow diagram of the proposed flood control method.

3 RESULTS OF SIMULATED DAM OPERATION UTILISING RAINFALL PREDICTION BY THE WRF MODEL

Using the method described in chapter 2, flood control simulation was conducted for 69 actual floods experienced by 12 dams. Table 1 shows the number of discharge operations to reach the harmless discharge rate, number of preliminary discharge operations implemented, number of discharge operations at the maximum design discharge rate and other data which were necessary for these simulations. The simulated flood control effects vary depending on

Table 1. Summary of simulation results.

Name of dam	Number of cases examined	Value used to judgge suitable operation	Number of cases: The discharge operation at a constant rate upto the harmless discharge rate was conducted*	Preliminary discharge took place	The discharge operation above the harmless discharge rate took place	The discharge rate exceeded the design maximum discharge rate	The dam capacity was completely used up	delayed operation took place	The water use capacity was not fully restored ****
Hoheikyo	12	maximum	11	0	1	1	1	0	9 (0)
		prediction	11	0	1	1	1	0	9 (0)
		minimum	11	0	1	1	1	0	9 (0)
		Actual operation	9	0	3	1	0	0	9
Shijyushida	7	maximum	6	4	1	0	0	1**	4 (2)
		prediction	6	2	1	0	0	0	4 (0)
		minimum	7	0	0	0	0	0	4 (0)
		Actual operation	4	0	3	0	0	0	1
Kawamata	6	maximum	6	0	0	0	0	0	5 (0)
		prediction	6	0	0	0	0	0	5 (0)
		minimum	6	0	0	0	0	0	5 (0)
		Actual operation	5	0	1	1	0	0	3
Yahagi	14	maximum	13	10	1	0	0	0	13 (9)
		prediction	13	1	1	0	1	0	12 (1)
		minimum	14	0	0	0	1	0	12 (0)
		Actual operation	8	0	6	1	0	0	8
Nukui	4	maximum	4	0	0	0	0	0	1 (0)
		prediction	4	0	0	0	0	0	1 (0)
		minimum	4	0	0	0	0	0	1 (0)
		Actual operation	3	0	1	0	0	0	0
Sameura	10	maximum	9	1	1	0	1	8***	4 (0)
		prediction	9	0	1	0	1	7	4 (0)
		minimum	9	0	1	0	1	7	4 (0)
		Actual operation	5	0	5	0	0	0	4
Tsuruda	11	maximum	3	11	8	1	1	1	1 (1)
		prediction	7	9	4	1	2	1	1 (1)
		minimum	5	3	6	1	5	0	1 (0)
		Actual operation	0	0	11	1	0	0	1
Nibutani	1	maximum	0	1	1	1	1	0	0
		prediction	0	0	1	1	1	0	0
		minimum	0	0	1	1	1	0	0
		Actual operation	0	0	1	1	1	0	0
Kanogawa	1	maximum	0	1	1	0	0	1	0
		prediction	0	0	1	0	1	1	0
		minimum	0	0	1	0	1	1	0
		Actual operation	0	0	1	0	1	0	0
Nomura	1	maximum	1	1	0	0	0	0	1 (1)
		prediction	1	1	0	0	0	0	0
		minimum	0	0	1	0	0	0	0
		Actual operation	0	0	1	0	0	0	0
Dokawa	1	maximum	0	1	1	1	0	1	0
		prediction	0	0	1	1	0	1	0
		minimum	0	0	1	1	1	1	0
		Actual operation	0	0	1	1	0	1	0
Hohri	1	maximum	0	0	1	1	1	0	0
		prediction	0	0	1	1	1	0	0
		minimum	0	0	1	1	1	0	0
		Actual operation	0	0	1	1	1	0	0
Total	69	maximum	53	30	16	5	5	12	38 (13)
		prediction	57	13	12	5	8	10	36 (2)
		minimum	56	3	13	5	12	9	36
		Actual operation	34	0	35	7	3	1	26

* The number of cases with a constant discharge rate of up to the harmless discharge rate includes those cases where the flood inflow rate failed to reach the harmless discharge rate (not depending on the set prediction error range). The actual number of such cases was 2 for Shijyushi Dam, 2 for Kawamata dam, 1 for Yahagi Dam and 2 for Nukui Dam.

** Delayed operation was due to lowering of the water level, in turn caused by preliminary discharge.

*** Because of the absence of a conduit gate, Sameura Dam experiences operational delay when the wa-ter level is below the control level (crest gate bed height). Although the August, 2004 flood exceeded the crest gate bed height, the discharge capacity was not raised due to the deep water depth.

**** The number of cases where flood control operation ended with the reservoir level remaining below the control level (of these, the number of cases where preliminary discharge was conducted).

Table 2. Comparison between simulated operation based on the WRF model and actual operation performed.

Name of dam	Flood	Maximum inflow rate (m^3/s)	Maximum discharge rate (m^3/s) Actual	WRF model	Reduction (m^3/s)
Yahagi	Sep. 2000	2993	2378	974	1404
Nibutani	Aug. 2003	5959	5489	5000	489
Dokawa	Aug. 2004	1005	827	712	115

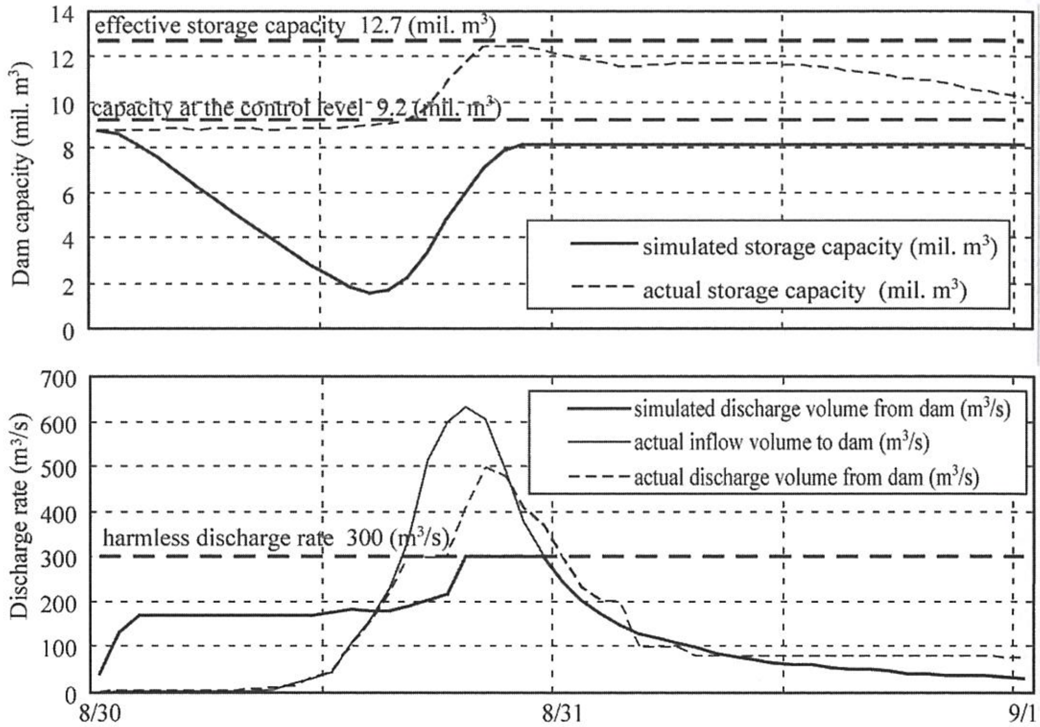


Figure 2. Case of maximum value (1.43 times higher than the WRF predicted value) for the August, 2004 flood involving Nomura dam.

the use of the predicted rainfall value by the WRF model, maximum value or minimum value. Analysis of the simulation results has clarified the following points.

1. In the case of an excess flood, the damage can be minimized by means of deciding appropriate preliminary discharge operation and maximum discharge rate based on rainfall prediction. On the three excess floods flooded downstream of dams, the respective predicted rainfall values by the WRF model in Table 2 suggest the maximum discharge rate is significantly reduced and a substantial alleviation of the flood damage.
2. The general trend is that preliminary discharge operation or discharge more than the harmless discharge rate was often conducted in those cases where the maximum value was used. Regarding many of those cases where the minimum value was used, the entire dam capacity is completely spent.
3. Of the 69 floods involving 12 dams used for simulation, only harmless discharge rate operation as a result of preliminary discharge, etc. was required for 50 plus smaller floods regardless of either the maximum value or minimum value being used. In reality, discharge operation at or below the harmless discharge rate was conducted with only 34 floods.
4. In the case of using the maximum value in August, 2004 flood at Nomura Dam, the excessive level of predicted rainfall necessitated massive preliminary discharge operation, resulting in failure to fulfill the full capacity for water use in the aftermath of the flood as

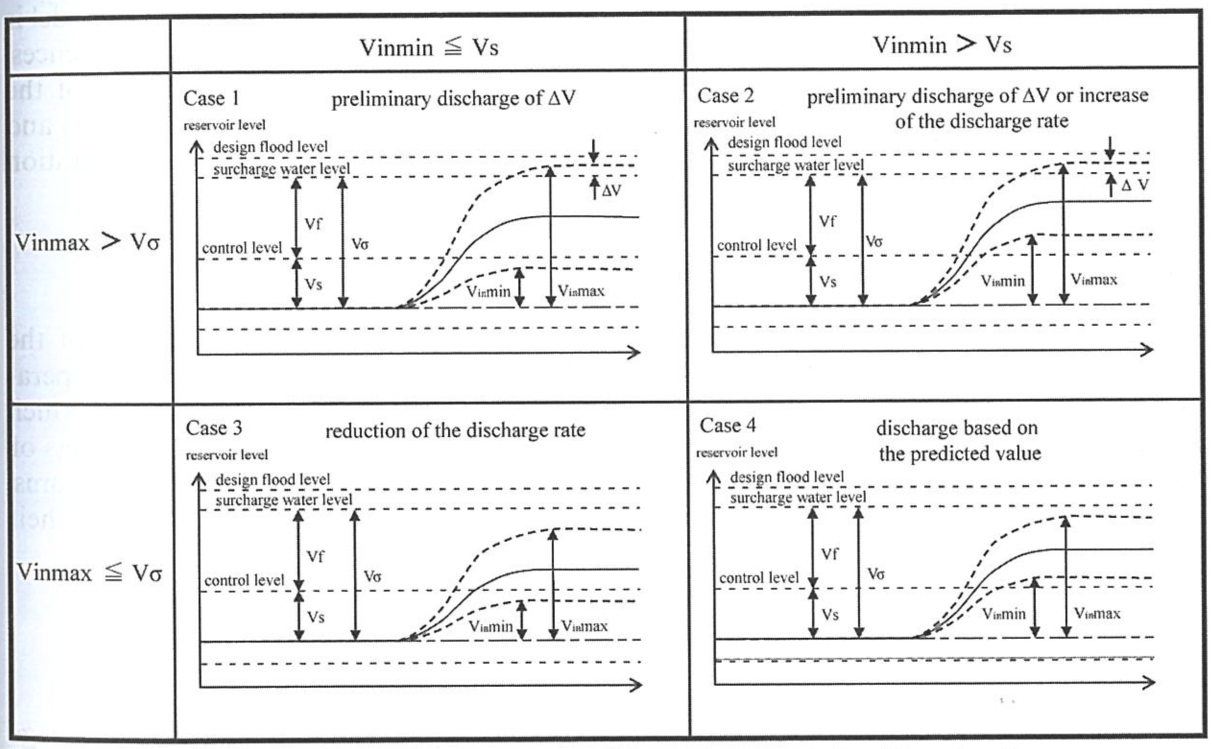
shown in Figure 2. When the predicted value by the WRF model or the minimum value was used for the same flood, no such negative effect from the viewpoint of water use occurred.

4 IMPROVEMENT OF THE METHOD FOR ITS PRACTICAL APPLICATION TO DAM MANAGEMENT

The simulations described in chapter 3 established that errors in rainfall prediction can result in the prediction of a much higher or lower volume of inflow to a dam reservoir than the actual volume and affect the performance of such dam functions for flood control and water use as preliminary discharge and fulfillment of the unfulfilled water use capacity. For practical dam management, it is essential to accurately understand possible errors in rainfall prediction by the WRF model and to formulate appropriate responses, considering the risks posed by prediction errors (response to deal with excess flood which may result from an actual rainfall level exceeding the predicted level or a need to fulfill the unfulfilled water use capacity as a result of a lower than predicted actual rainfall level). To be more precise, the following improvement and clarification are required.

4.1 *Improvement of the operation method*

When a prediction range is set for actual dam operation in consideration of rainfall prediction errors, there can be cases where such contradictory operation as preliminary discharge operation and harmless discharge rate operation are judged to be necessary according to the flow diagram shown in Figure 1. To be more precise, there are four different cases as shown in Figure 3 when the normal dam operation rules are followed. In Figure 3, the inferred reservoir



V_f:	flood control capacity	V_{in}max:	reservoir level based on the maximum WRF prediction value
V_s:	available capacity for water use at the time of prediction		
$V_\sigma = V_f + V_s$:	available capacity at the time of prediction	V_{in}min:	reservoir level based on the minimum WRF prediction value

Figure 3. Classification of reservoir water level and discharge operation based on rainfall prediction errors.

water level is shown for each of the predicted, maximum and minimum rainfall levels when normal dam operation stipulated by the dam operation rules is conducted. In Case1, rainfall at the maximum value causes an insufficient flood control capacity while rainfall at the minimum value causes non-fulfillment of the water use capacity. In this scenario, the flood control function and water use function work against each other. Assuming that the actual rainfall is within the prediction error range used in this paper, it must be realized that discharge above the design discharge rate could cause serious damage while non-fulfillment of the unfulfilled water use capacity does not necessarily cause immediate damage apart from a negative impact on power generating operation. The highest priority should, therefore, be given to the alleviation of likely flood damage downstream. Once the priority of flood control over water use is accepted, preliminary discharge corresponding to the volume ΔV, which is above the flood control capacity, should be conducted as indicated in Figure 1. In Case 2, preliminary discharge corresponding to the volume of ΔV is necessary as in Case 1. In Case 3, rainfall at the minimum value causes disruption to water use. Here, even if rainfall at the maximum value occurs, the required dam operation is to try to restore the unfulfilled water use capacity so long as the available flood control capacity does not become insufficient. No operational problems are experienced with Case 4. For practical dam management, adequate judgment must be made in consideration of such possible negative impacts as an insufficient flood control capacity and the non-fulfillment of the unfulfilled water use capacity due to rainfall prediction errors of the WRF model on the flood control and water use functions.

4.2 *Clarification of rainfall prediction errors of the WRF model*

The study results on error rates (Wada, 2006), which are referred to in chapter 2 and used for convenience for the simulations described in chapter 3, indicate the maximum and minimum values of the error range for rainfall predictions made by the Japan Meteorological Agency for actual rainfall levels observed by using a 20 km mesh static model which features a limited number of observation stations and precipitation events. In contrast, the WRF model is non-static and involves down-scaling to a minimum 1 km mesh. Because of these differences, it is necessary to clarify the characteristics of prediction errors through comparison of the predicted rainfall levels of the WRF model and actual rainfall levels for as many dams and floods as possible prior to the application of the WRF model to practical dam operation management.

4.3 *Improvement of facilities*

In case that the discharge capacity of dams is small under low water levels because of the limitation of discharge capacities of bottom outlets, it is difficult to conduct smooth operation to increase the discharge rate to meet the inflow rate or preliminary discharge which mitigates flooding at the time of excess flood effectively and the expected positive effects of the simulation exercise described in chapter 3 cannot be fully materialized. With these dams, remodelling, such as installing an additional bottom outlet, can be expected to improve their flood control function.

5 CONCLUSIONS

The study has proposed a simple flood control method in order to minimize flood damage downstream by the integrated operation of the flood control and the water use capacities of dams by forecasting the total inflow volume to a dam using the rainfall prediction method based on WRF techniques which have significantly improved in recent years. The effectiveness of this method was examined using actual data on rainfall, flood and dam operation events. Assuming that the rainfall prediction errors of the WRF model are within the error range used by the study for convenience, the following conclusions are presented.

1. The proposed method enables the prediction of the total inflow volume to a dam within a certain period of time. It is, therefore, possible to alleviate flood damage in many cases by means of conducting preliminary discharge, etc., to lower the maximum discharge rate than the discharge rate stipulated by the existing exceptional rule for dam operation even if an excess flood has taken place.
2. For many smaller floods, the application of the new method can prevent flood damage downstream as the discharge rate remains below the harmless discharge rate.
3. The actual use of rainfall prediction by the WRF model can enhance the effectiveness of flood control function but there are also risks posed by prediction errors. It is necessary to accurately understand the characteristics of the new model, including possible rainfall prediction errors. To minimize these risks any judgment on the flood control operation should reflect the characteristics.
4. For those dams where the capacity of the crest spillway gates and other flood control facilities is insufficient, their remodelling can be expected to achieve certain positive results to ensure the effective implementation of preliminary discharge and other operations. It is, therefore, desirable to conduct adequate remodelling, taking into consideration the flood control capacity, water use capacity and situation of flood damage occurrence downstream.

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