Development of effective pre-release method for dams during super typhoons using long-term ensemble rainfall forecasts

Développement d'une méthode efficace de lâchers d'eau préventifs pour les barrages lors d'un super typhon par la prévision d'ensemble des précipitations à longue échéance

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Abstract. Against the background of increasing frequency of heavy rainfall due to climate change, an analytical approach to maximize the effective use of the reservoir from both flood control and water utilization was conducted. Simulations by applying statistical down-scaling method to the long-term ensemble rainfall forecast by ECMWF on a dam basin where a large inflow occurred during the Typhoon Hagibis in 2019 were shown. The results show that it is possible to use long-term ensemble rainfall forecasts to gain a temporal, stochastic understanding of total rainfall, required flood storage volumes, and recoverable reserves. Based on this understanding, a calculation method for setting release rates that correspond to effective pre-release start times and changes in rainfall forecasts in order to minimize both flood control and water service risks was proposed.

Résumé. Dans un contexte d'augmentation de la fréquence des fortes pluies dues au changement climatique, une approche analytique visant à maximiser l'utilisation efficace du réservoir à la fois pour le contrôle des crues et l'utilisation de l'eau a été menée. Des simulations en appliquant une méthode statistique de mise à l'échelle à la prévision à long terme des précipitations d'ensemble par ECMWF sur un bassin de barrage où un afflux important s'est produit pendant le typhon Hagibis en 2019 ont été présentées.

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Les résultats indiquent que la prévision d'ensemble des précipitations à longue échéance permet d'appréhender sous les angles chronologiques et stochastiques les précipitations totales ainsi que les volumes nécessaires de stockage de crue et potentiels de recharge des retenues. Sur cette base, une méthode de calcul pour fixer les taux de rejet qui correspondent aux heures de début effectives avant la libération et aux changements des prévisions de précipitations afin de minimiser à la fois le contrôle des crues et les risques liés au service de l'eau a été proposée.

1 Introduction

In recent years, severe heavy rain disasters have occurred throughout the world on an annual basis. The possibility of further increases in the frequency of torrential rainfall due to climate change has been pointed out by the Intergovernmental Panel on Climate Change (IPCC) (e.g., the Fifth Assessment Report [1]) and in other research. In Japan, research has been conducted regarding the use of ensemble rainfall forecasts to advance dam flood control methods (e.g., Inomata [2] and Kitani et al. [3]). However, in light of the intensification of rainfall in recent years, the need to develop technology to enable effective flood control by taking full advantage of existing dams has become even stronger [4,5].

Since 2018, the Disaster Prevention Research Institute of Kyoto University, the Japan Water Agency and the Japan Weather Association have been developing a support system for integrated disaster risk reduction for dams, specifically for super typhoons, as part of the Cross-ministerial Strategic Innovation Promotion Program (SIP) by the Cabinet Office of Japan.

One of the key concepts of the development is to maximize the effective use of the reservoir from both flood control and water utilization by using the long-term ensemble rainfall forecasts. Specifically, the necessary flood control capacity will be secured by setting the start timing of the pre-release and the release amount appropriately, and the released water will be effectively used for water service (power generation, irrigation and water supply) as much as possible.

In this study, rainfall data from the catchment area of a Model Dam in the Kanto region of Japan from Typhoon Hagibis in 2019 was used, and statistical downscaling techniques to long-term ensemble rainfall forecasts provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) was applied to conduct model analysis for the purpose of investigating the applicability of long-term ensemble rainfall forecasts and effective pre-release methods during the approaches of super typhoons.

The authors have presented another study (D. Nohara, K. Kitani, Y. Michihiro and T. Sumi, Decision support for preliminary release of reservoir for flood control using ECMWF medium-range ensemble rainfall forecast) at this symposium to apply ensemble rainfall forecasts to dams' pre-release. These studies are based on a common concept, but the specific approach is different for each study. In this study, the pre-release method for multipurpose (i.e., flood control and water use) dams is discussed, and that for dams for power generation is discussed in the study by Nohara et al. There are differences in the reservoir operation method and the concept of pre-release between these dams. A procedure for adaptive pre-release method for multipurpose dams that considers both risks to flood and water use is proposed in this study.

2 Overview of Typhoon Hagibis (2019)

Figure 1 shows the path of Typhoon Hagibis [6]. The defining characteristics of this typhoon were its development of intense energy immediately after forming, the lack of substantial weakening in its energy during its subsequent northward progression, and the retention of its extremely strong energy until it approached to the Kanto region of Japan.
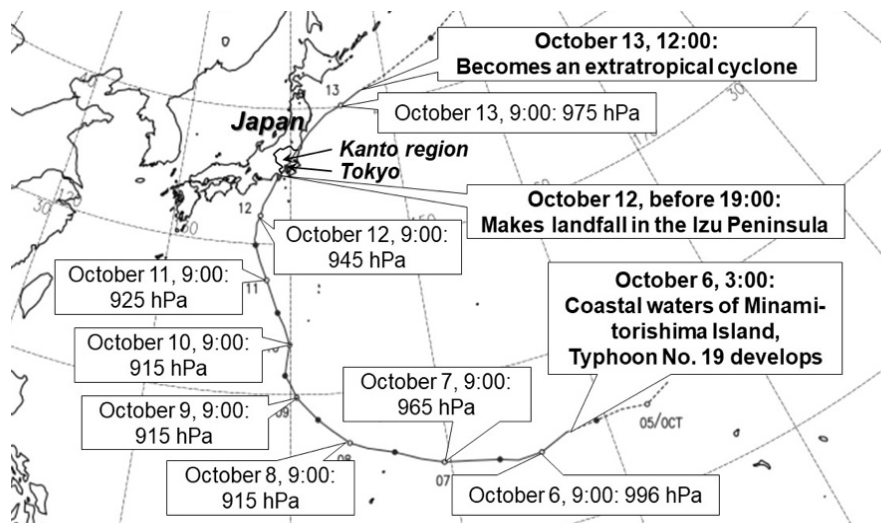

Fig. 1. Path of Typhoon Hagibis (revised from [6])

The catchment area of the Model Dam experienced cumulative rainfall of 513 mm (catchment area mean value from telemeter observations from 13:00 on October 11 to 4:00 on October 13), the highest figure since dam management began. The figure is equivalent to roughly 40% of the mean annual rainfall of roughly 1,300 mm for the catchment area. It is worth noting that the previous maximum rainfall observed during a flood since the start of Model Dam management (1969) was 435 mm (catchment area mean value from telemeter observations) brought by Typhoon Danas in 2001. The rainfall from Typhoon Hagibis far exceeded the previous maximum.

3 Analysis method

### 3.1 Overview of long-term ensemble rainfall forecast data

The long-term ensemble forecasts provided by ECMWF has the best specifications of all countries' operating models in terms of forecast times, spatial resolution, and number of ensemble members. The ECMWF ensemble contains 51 original members, forecasts in three-hour blocks up to 144 hours and six-hour blocks up to 360 hours, and has grid spacing of 0.25° longitude and latitude.

3.2 Frequency bias correction and statistical downscaling

The ECMWF and other ensembles contain errors in the modelling schemes for numerical weather projection models; they often underestimate the frequency of heavy rains as well as actual rainfall. Also, the tendency varies depending on the season and region. Therefore, in

this study, frequency bias correction was applied in reference to guidance materials from the Japan Meteorological Agency [7]. Correction factors were determined using data from autumn in the last three years in the scope of the analysis (2016-2018), and forecast data from October 2019 was corrected. The correction for each grid point in the model was performed, and correction factors were determined to make the frequency distributions of projected rainfall from the ECMWF ensemble in the nine cells surrounding each grid point match the frequency distributions of analysed rainfall from the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

The original 25-km grid was not precise enough for the Model Dam catchment area (323 km2); thus, there is a high possibility that the topographic effects around the dam is not sufficiently reflected. Therefore, by converting the grid to a 1-km grid via statistical downscaling with a lighter computational load [8], the mean rainfall for the Model Dam catchment area was calculated (Figure 2).
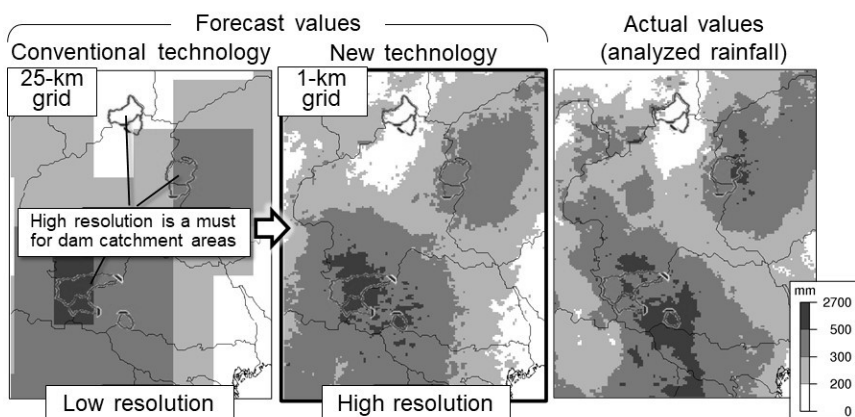
Cumulative rainfall for the 84-hour period from 21:00 on Oct.10 to 9:00 on Oct.14, 2019

Fig. 2. High-resolution conversion using statistical downscaling.

3.3 Analysis periods and cases

Thirty 12-hour blocks of forecast data starting from 0:00 on September 30 to 9:00 on October 15 were used. For the analysis cases for each 12-hour block, the 51 ensemble members and the mean of the upper (1st to 5th), middle (6th to 46th), and lower (47th to 51st) rainfall totals of the 51 members (for expediency, "Upper Ensemble," "Middle Ensemble," and "Lower Ensemble," respectively) were used.

Note that techniques have not been established at this point in time for configuring representative cases that properly express the maximum and minimum variation of the 51 members. In this study, the aforementioned Upper and Lower Ensembles were used as a simple method. Regarding this point, there is a need to continue to repeatedly verify analysis cases in the future.

3.4 Runoff analysis

For runoff analysis, a storage function model that divides the Model Dam catchment area into four parts based on the rainfall observation points was used. The calculation period was set to September 28, 2019, to 9:00 on October 15. Analysed rainfall from the MLIT was used for actual rainfall leading to the start time for forecasting in each case. Three-hour and six-hour rainfall data were divided into equal one-hour blocks.

4 Results of analysis

4.1 Total rainfall

The mean total rainfall for the catchment area from 0:00 on October 7 to 9:00 on October 15 for the 51 ensemble members as well as each of the Upper, Middle, and Lower Ensembles were calculated. Figure 3 shows the trends for each. Here, for forecasts done at or before 0:00 on October 7, total rainfall is the sum of forecasted rainfall from 0:00 on October 7 to 9:00 on October 15; for forecasts done after 0:00 on October 7, total rainfall is the sum of actual rainfall after 0:00 on October 7 to the time of the forecast and forecasted rainfall from the time of the forecast to 9:00 on October 15. In Figure 3, the 54 total rainfall data points (the 51 ensemble members and the Upper, Middle, and Lower Ensembles) are plotted vertically for each forecast time.
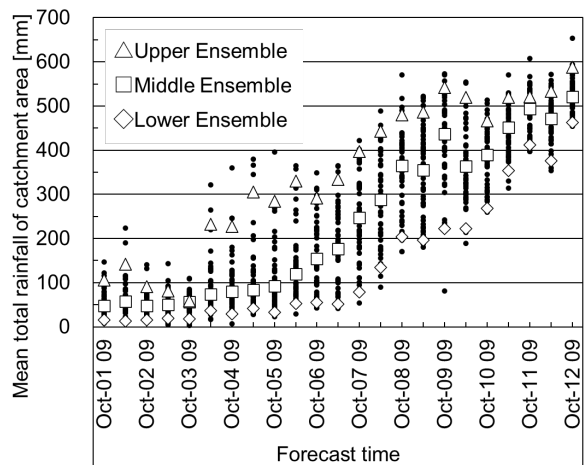

Fig. 3. Changes in mean total rainfall of model dam catchment area.

According to the data, members with total rainfall exceeding 300 mm began to appear at 21:00 on October 3 (nine days before the typhoon made landfall), and the total rainfall distribution trended upward after that. On October 8, the lowest total rainfall expected was in the 200-mm range, with rainfall in the 500-mm range expected at most points. Although the Upper Ensemble essentially stayed flat from that point on, the Lower Ensemble trended upward, narrowing the gap between it and the Upper Ensemble (the range of forecast values). The forecast values increased sharply from 21:00 on October 11 to 9:00 on October 12 (roughly 10 hours before the typhoon made landfall), with total rainfall of 450 to 600 mm expected at most points.

It is worth noting that the Japan Meteorological Agency's Global Spectral Model (GSM) and MesoScale Model (MSM) forecast total rainfall of 296 mm, 441 mm, and 548 mm for 12:00 on October 10, 17:00 on October 11, and 8:00 on October 12, respectively. According to Figure 3, these figures are roughly equivalent to the Lower to Middle Ensemble.

4.2 Required flood storage volume

Figure 4 shows the expected required flood storage volumes calculated by the flood control rule of the Model Dam using the rainfall time history data for each time, ensemble member,

and the Upper, Middle, and Lower Ensembles (Figure 3). According to the data, trends in Upper Ensemble values showed flood storage occurring in forecasts at and after 9:00 on October 5, as well as the possibility that flood storage volume would already exceed flood control capacity (35,000,000 m^3) before 9:00 on October 7. Subsequently, Upper Ensemble flood storage fluctuated while trending upward to an expected level of roughly 70,000,000 m^3 to 80,000,000 m^3. Furthermore, a sharp increase in flood storage was forecast at 9:00 on October 12, resulting in the possibility of a maximum of roughly 95,000,000 m^3. On the other hand, trends in Lower Ensemble values indicated the possibility of no flood storage occurring until 21:00 on October 9. However, the values increased sharply thereafter; forecasts on October 11 called for the flood storage volume to exceed the flood control capacity, with a further increase forecast at 9:00 on October 12.
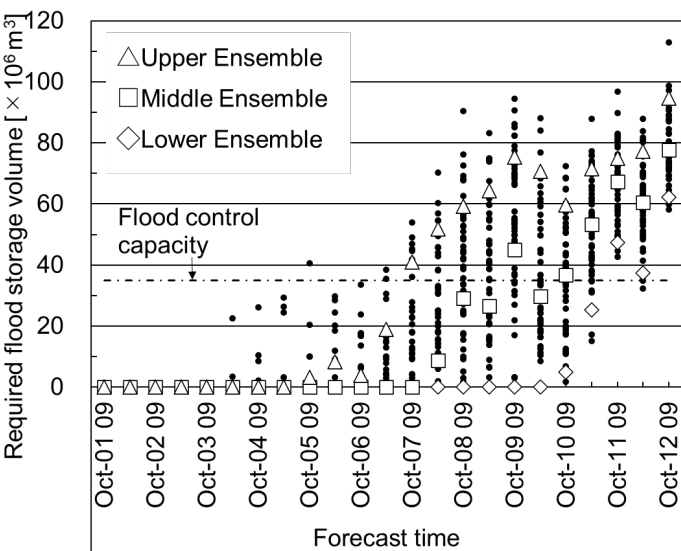

Fig. 4. Changes in required flood storage volume.

4.3 Recoverable volume

Using the same runoff calculation as in Section 4.2, the amount of water that can be stored for water use during/after flood control was calculated. The calculation method followed the approach shown in Figure 5 [9]. The base flow rate was set to 16 m^3/s. In cases when the peak inflow rate was less than the flood rate (set to 500 m^3/s), the inflow in excess of the base flow rate after peak inflow was calculated as recoverable volume. Figure 6 shows the trends in these forecast values. In terms of water use, when making the decision to pre-release water from a dam, it is necessary to pay attention to trends in the minimum variation of forecast values (the least extent to which recovery can be expected with certainty).
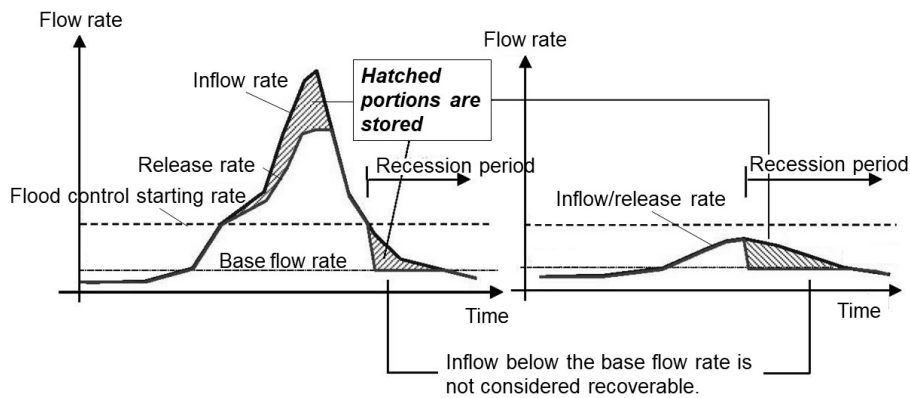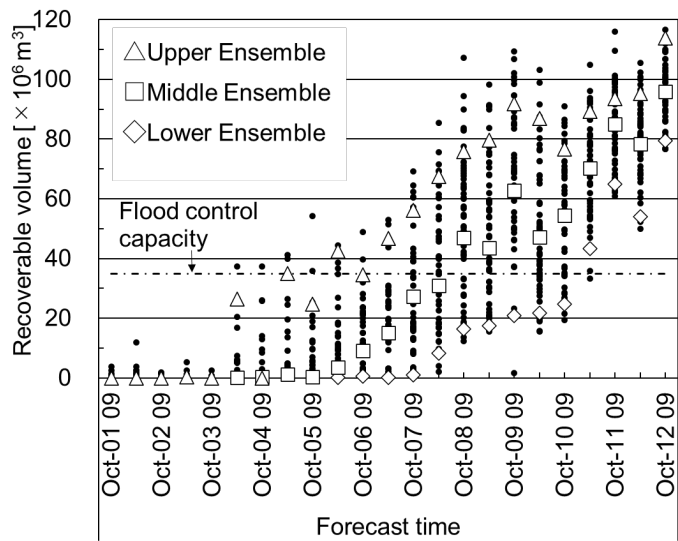
Fig. 5. Approach to recoverable volume [9].

Fig. 6. Changes in recoverable volume.

5 Pre-release methods using long-term ensemble forecasts

5.1 Key points in pre-release of multipurpose dams

Generally, in multipurpose dams, the flood control capacity is set above the water service capacity. Therefore, inflow in excess of the flood control capacity must be released using one or both of the following methods: (1) releasing the equivalent volume from within the water service capacity in advance (pre-release), and/or (2) increasing the release rate during the flood control period using operations other than the regulated release methods in flood control plans. However, the latter should be avoided whenever possible because it further increases the flow rates of downstream rivers during the flood, increasing the possibility that they will overflow.

Since the pre-release is performed using the runoff analysis based on the rainfall forecasts several days ahead, it is necessary to consider the uncertainty due to error and fluctuation of the forecasts. Therefore, when planning for pre-release of a multipurpose dam, two risks

should be considered; a "risk in flood" where the flood control capacity including the pre-released volume is insufficient, and a "risk in water use" where the water released from water service capacity cannot be recovered after the flood. It is required to make both of them as small as possible.

In addition, pre-release is an operation to increase the river flow when the river is still in a normal state before flooding. Therefore, in order to reduce the impacts on the use in downstream river (e.g., fishery, water intake, recreation) and on the local community, it is also important to carry out pre-release in a planned and stepwise manner while suppressing sudden changes in the flow rate.

In consideration of these key points, a procedure for setting appropriate pre-release volume and flow rate to avoid exceeding the flood control capacity while ensuring the certainty of water storage recovery as much as possible is discussed in the following sections.

5.2 Pre-release start times and stage classification

Figure 7 shows the trends of required flood storage volume and recoverable volume from the Upper and Lower Ensembles extracted from Figures 4 and 6, portrayed on the same graph. Here, zero on the horizontal axis is 9:00 on October 12 (the start of flood control), with the time leading to it expressed in negative numbers. Note that the actual start time of flood control at the Model Dams was around 10:30 on October 12. This allows us to consider changes that occurred as the typhoon approached in the following stages.
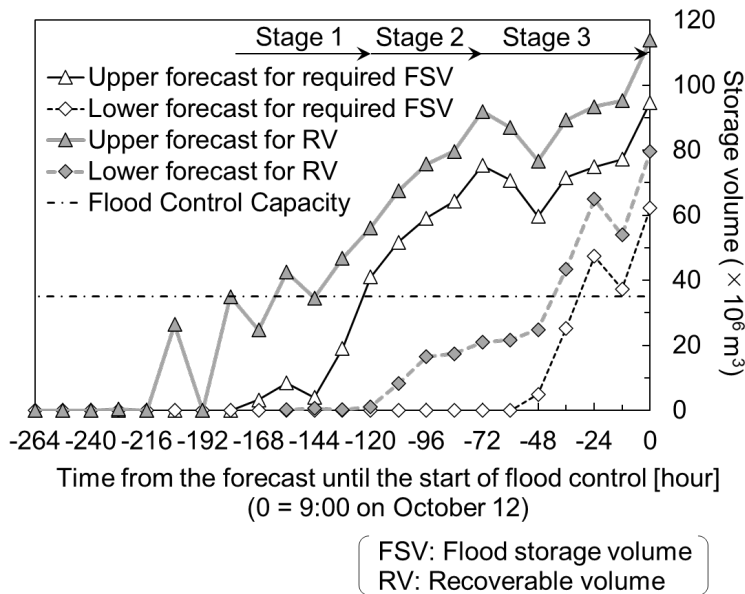

Fig. 7. Changes in required flood storage volume and recoverable volume.

5.2.1 Stage 1

Stage 1 is the stage in which the upper required flood storage volume increases, presenting the possibility of flood storage. However, the upper required flood storage volume is lower than the flood control capacity. In contrast, the lower recoverable volume is small; the prospect of recovery is not certain. In Figure 7, Stage 1 corresponds to the period from 180 hours (7.5 days) to 120 hours (five days) before the start of flood control.

Pre-release is not strictly necessary during this stage, but if the reserve is within the flood control capacity in the non-flood season, the best course of action is to begin releasing water stored in the flood control capacity (this is known as a "preliminary release") to increase the available flood control capacity. In this case, it is possible to use the upper required flood storage volume as a target for the preliminary release volume. Additionally, when possible, the best course of action is to release water (pre-release) with respect to the reserve within the water service capacity to ensure as much extra capacity for flood storage as possible, all while paying attention to the development and approach of typhoons and other changes in meteorological conditions. In this stage, the range of the volume for water service should be an appropriate upper limit for the pre-release rate.

5.2.2 Stage 2

Stage 2 is the stage in which the upper required flood storage volume exceeds the flood control capacity, presenting the possible need for pre-release. In Figure 7, Stage 2 corresponds to the period starting 120 hours before the start of flood control. However, changes in forecast values and the range between upper and lower are still substantial in this stage; finally, it is difficult to be certain of the pre-release volume that will be needed.

Present protocol of Japan [10] calls for the use of the Japan Meteorological Agency's Global Spectral Model (GSM, forecasts up to 84 hours) to forecast the amount of rain to be used in decisions about pre-release. Supposing a duration of rainfall of at least half a day, the target GSM rainfall forecasts can be used as early as roughly 72 hours before the forecast start time of the rainfall. Thus, in this study, Stage 2 was set from the point in time at which the possible need for pre-release is presented until 72 hours before the start of flood control. A method for starting pre-release at an earlier time using long-term ensemble rainfall forecasts and making the pre-release volume approach the limit of the requisite pre-release volume incrementally as explained in Section 5.3 was devised in consideration of changes to the forecasts and extra time until the start of flood control.

5.2.3 Stage 3

Stage 3 is the final adjustment stage, from 72 hours before the start of flood control to the start of flood control. In this stage, it is critical to ensure the final required pre-release volume while forecasting and adjusting the release rate in shorter time intervals based on various meteorological forecast data. (Note: In this study, only ensemble rainfall forecast data updated every 12 hours to do trial calculations was used.)

The upper limit of the pre-release rate is determined with respect to the flood rate, the impact on river use downstream of dams, stability of slopes surrounding reservoirs, outlet capacity, and other conditions unique to individual dams. Accordingly, during Stage 2, the timing of the switch to the maximum release rate with respect to time remaining must be forecast each time the forecast for required pre-release rate is updated, and depending on the circumstances, it may be necessary to transition to Stage 3 earlier than 72 hours before the start of flood control.

5.3 Ensemble pre-release

The authors devised a method for calculating release rates to ensure the requisite pre-release volume while adjusting the pre-release rate based on constantly updated ensemble forecast data in Stages 2 and 3. We call the method of pre-release based on this approach "ensemble pre-release," that is, a method of using long-term ensemble rainfall forecasts to ensure the

optimal pre-release volume while adaptively adjusting release rates to the range and variation of the forecasts.

Supposing a target time for the start of flood control T, the pre-release volume $\Delta V(t)$ from a given time t until the next forecast update (t_a hours later, hereinafter referred to as "the forecast update interval") is defined by the following equation.

$$\Delta V(t) = \frac{V_E(t) - V(t)}{T - t} \cdot t_a \qquad (1)$$

Additionally, $\Delta V(t)$ must satisfy the following equation to prevent the pre-release volume from exceeding the forecast recoverable volume at time t until the next forecast update interval.

$$\Delta V(t) \le V_R(t) - V(t) \qquad (2)$$

Here,
$\Delta V(t)$: Pre-release volume from time t until the next forecast update ($t + t_a$) [m^3]
$V(t)$: Total pre-release volume until time t [m^3]
$V_E(t)$: Upper forecast for excess of flood control capacity at time t [m^3]
$V_R(t)$: Lower Forecast for recoverable volume at time t [m^3]
T: Target time [hours]
t: Forecast time [hours]
t_a: Forecast update interval [hours]

Note that when $\Delta V(t)$ as defined in Equations (1) and/or (2) is negative, pre-release should be suspended temporarily, and subsequent forecast trends should be used to determine whether to resume the release of water, maintain reservoir levels or recover reserves.

Figure 8 is an illustration of the setting of pre-release rates based on Equations (1) and (2). Here, as shown in Figure 8, the pre-release volume to ensure at target time T is determined according to the forecast data from the previous interval ($T - t_a$). In the following calculations, target time T is set in two stages: the timing of the transition from Stage 2 to Stage 3 ($T = -72$ hours) and 12 hours before the start of flood control. In other words, the pre-release volume to ensure at the transition from Stage 2 to Stage 3 is the equivalent of the smaller of the recoverable volume or the volume in excess of flood control capacity at $T = -84$ hours.
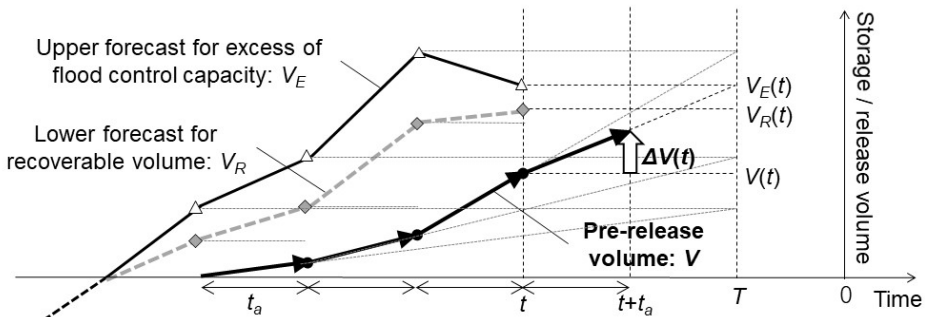

Fig. 8. Image of the ensemble pre-release method.

The target time may be changed in response to factors such as trends in forecasts. Additionally, the target pre-release volume at the transition from Stage 2 to Stage 3 can be set lower or otherwise adjusted to account for uncertainty in trends in forecasts. However, in pursuit of using reserves for water services as long as possible, and given factors such as the certainty of actions to take in response to sharp increases in forecast values, the best course of action appears to be setting a high pre-release volume within the recoverable volume until Stage 2. Note that the pre-release volume to be finally ensured is decided and determined considering the situations comprehensively, i.e., the latest forecast data (immediately before the start of flood control) and conditions of the dam and the river.

5.4 Calculation results

Figure 9 is the result of using the method shown in Figure 8 to calculate the pre-release volume for each forecast update interval based on the graph in Figure 7, which shows both the lower recoverable volume and the line representing the volume in excess of upper flood control capacity determined by subtracting the flood control capacity from the upper required flood storage volume.

Here, Case 1 is the result of calculations to determine the arithmetic release rate corresponding to the time remaining until the target times in Equation (1) and (2) (72 and 12 hours before the start of flood control). This demonstrates that it is possible to incrementally and cumulatively ensure the expected pre-release volume required at the start of flood control while adjusting release rates at each interval using the method shown in Figure 8. However, substantial variance in forecast values (volumes in excess of flood control capacity or recoverable volumes) results in variance of release rates at each interval.
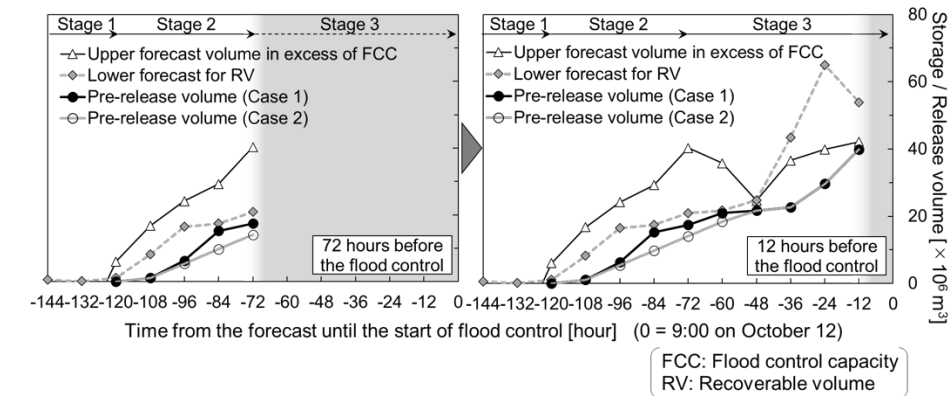

Fig. 9.a. Calculations of pre-release volume and rates - Pre-release volume.
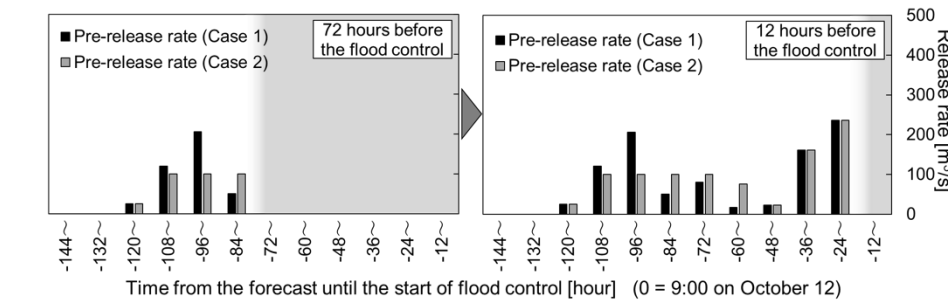

Fig. 9.b. Calculations of pre-release volume and rates - Pre-release rate at each interval.

Water is pre-released from dams several days before typhoons approach, meaning that it is done when the weather and state of streamflow are calm and normal. Therefore, upper limits and fluctuation of release rates should be controlled to the extent possible in consideration of the impact on factors such as water usage downstream and other water service aspects, river use at those times, and dam operations.

Case 2 is the result of calculations performed with the maximum release rate in Stage 2 set to 100 m³/s. Here, the upper limit value was set to 100 m³/s as a temporary guideline in this study referring to that the upper limit of the "flash release" (temporarily increasing the dam release implemented in normal weather conditions for improving the downstream river environment) performed in the Model Dam is set to 90 m³/s.

Variation in the release rate is more limited in Case 2 than in Case 1, facilitating more consistent pre-release operations. However, in Case 2, it was not possible to ensure the target pre-release of volume, which was the pre-release volume at 72 hours before the start of flood control in Case 1. Further investigation is required into matters such as smoothing out release rates with respect to variation in forecasts and methods for setting reasonable targets.

6 Conclusions

The following outcomes were achieved from this study: 1) The ECMWF's 15-day ensemble rainfall forecast data can be used to conduct runoff analysis of the 51 members in 12-hour blocks by applying spatiotemporal downscaling techniques in order to gain an understanding of how total rainfall and the required flood storage volume and recoverable volume of dams change with respect to the distribution of forecast values as typhoons approach. 2) Vital criteria for pre-releasing water from dams—specifically, the possibility of the required flood storage volume exceeding the flood control capacity, and recoverability with respect to the pre-release volume—can be expressed in simple terms through the proper setting of the upper and lower ranges of the above-mentioned forecast value distribution. 3) Based on 2), the authors devised "ensemble pre-release," a method of setting and adjusting release rates focused on the amount of time remaining until the target time, in three stages defined according to the possibility of the need for pre-release, the certainty of recovering reserves, and the amount of time until the start of flood control. Ensemble pre-release makes it possible to keep release rates relatively stable in response to variation in forecasts, facilitating more consistent pre-release operations. 4) Further investigation is required into matters such as setting of the upper and lower ranges described in 2), smoothing out release rates with respect to variation in forecasts and methods for setting reasonable targets.

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