

# **A framework to assess effectiveness and risks of integrated reservoir operation for flood management considering ensemble hydrological prediction**

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## **Abstract**

A Monte Carlo-based method to analyze effectiveness and risks of integrated operation of a multi-purpose reservoir for flood management considering real-time ensemble hydrological predictions is developed. Preliminary release operation, in which water stored in the reservoir is released just before a flood event considering real-time hydrological predictions to secure more empty volume in the reservoir for flood protection, is considered as an integrated reservoir operation method here. The analysis provides reservoir managers with quantitative and science-based information on expected benefits and risks to introduce operational hydrological predictions into reservoir operation from the long-term viewpoint.

## **1. INTRODUCTION**

Effective water resources management is needed in order to mitigate impacts of severe water-related disasters. As reservoirs can play an important role in water resources management, sophistication of reservoir operation can enhance the capability of existing water resources management systems to withstand severe floods and droughts. Multi-purpose reservoirs, which regulate river flow for both of water use and flood protection, are especially expected to have an ability to contribute to more effective water resources management.

On the other hand, various operational hydrological predictions have been provided by meteorological or hydrological authorities in many regions. Operation of reservoir systems can be considered to be improved by utilizing these hydrological predictions as reservoirs can be operated in more adaptive manner considering the expected hydrological conditions in the target river basin. There is, however, no prediction system which provides perfect predictions, and hydrological predictions therefore contain uncertainty inherently. If a hydrological prediction considered in

reservoir operation is false, the operation may bring adverse consequences in water resources management in the target river basin. In this manner, prediction uncertainty often makes it difficult to use hydrological predictions in real-time reservoir operation.

As a method to deal with prediction uncertainty, the ensemble prediction technique, which conducts multiple numerical forecasts with different initial conditions, have been introduced into operational hydrological predictions in many regions. Since ensemble hydrological prediction provides multiple prediction sequences, one can derive not only an averaged hydrological condition predicted but also possible hydrological scenarios, with which prediction uncertainty can be estimated by seeing distribution or variance of the situations predicted by the scenarios. Such information on uncertainty of prediction can be considered important for more robust decision making in real-time reservoir operation.

From the viewpoint that introduction of ensemble hydrological predictions has a potential to improve real-time reservoir operation, various studies have been conducted to investigate effectiveness of reservoir operation considering ensemble hydrological predictions. Faber & Stedinger (2001) developed an optimization method for an existing reservoir system for drought management considering operational ensemble streamflow prediction derived from ensemble streamflow prediction of the United States National Weather Service. Kim *et al.* (2007) investigated the effectiveness of an optimization model for operational policies of Korean multi-reservoir system by using dynamic programming (DP) models with ensemble streamflow prediction. Nohara *et al.* (2009) analyzed applicability of operational one-month ensemble forecast of precipitation provided by Japan Meteorological Agency (JMA) for advanced operation of reservoir for water supply considering DP models.

As seen in the past studies listed above, effectiveness of ensemble hydrological predictions have been investigated mainly for long-term reservoir operation for water utilization purposes because ensemble prediction technique is introduced mainly into mid- or long-term operational hydrological forecasts where deterministic prediction is difficult due to long lead time of prediction. However, it can be considered that short-term reservoir operation for flood management can also be enhanced by considering ensemble hydrological predictions especially with medium temporal ranges, from several days to a week, which can cover the duration of a flood event. Multiple prediction scenarios included in an ensemble hydrological prediction can also be considered useful to assess expected benefits or risks when a reservoir is operated for flood management.

Considering the circumstances described above, a framework to assess the effectiveness and risks of integrated reservoir operation for flood management considering ensemble hydrological predictions is proposed in this study. Preliminary

release operation, which releases storage water from a multi-purpose reservoir just before a flood to secure increased amount of empty storage volume in the reservoir for flood control, is considered as an integrated reservoir operation method here. A Monte Carlo simulation of preliminary release and flood control operations of a reservoir is conducted for assessment of effects of reservoir operation when an ensemble hydrological prediction is introduced, employing multiple sets of ensemble hydrological predictions artificially generated with a designed error structures.

## 2. OUTLINE

### 2.1 Preliminary release operation of multi-purpose reservoirs in Japan

Securing more empty storage capacity enlarges the ability of a reservoir to control flood waters. Many reservoirs in Japan therefore has restriction in water storage to decrease their water level in summer and early autumn, when floods often occur due to heavy rainfall, so that they can effectively control flood waters in the river by storing water with the secured empty capacity in case of a flood event. However, river basins experience drought events frequently also from late spring to early autumn in Japan, as water consumption for irrigation increases in this period. Therefore, it may cause adverse impacts on water utilization such as water supply or power generation especially for multi-purpose reservoirs to keep low water level for flood management in this period. In order to balance needs for both the flood management and water utilization purposes, preliminary release operation has been introduced into multi-purpose reservoirs in the river basins prone to suffer from both floods and droughts in Japan.

In preliminary release operation, a reservoir basically keeps water level as high as possible for water utilization unless a flood is expected. When a flood is expected in the river basin where the reservoir locates, water level of the reservoir is decreased to a designated level by releasing water from the reservoir in advance of the flood in order to secure empty storage volume for flood control. Storage water level is then recovered by storing water discharged during the flood event for preparing for water supply after the flood event.

Because it usually takes time to complete decreasing water in the reservoir from the full storage level to a restricted level for flood control, reservoir managers need to estimate future hydrological conditions in order to make a decision for conducting preliminary release operation adequately in advance of a flood. Real-time hydrological predictions therefore play a significant role in this operation. Hydrological predictions for the coming one week are especially effective in this operation to estimate the timing and scale of a flood event before the flood, as most flood events last several days to a week in Japan. It is also considered important to take prediction

Table 1: Spec of One-week Ensemble Forecast of JMA considered in this study (as of February in 2013, corresponding to case study period).

Items	Values
Spatial range	22.5°N-71.25 °N, 90°E-180 °E (Japan Area)
Spatial resolution	1.25° grid
Temporal range	192 hours (8 days)
Temporal resolution	6 hours
Update frequency	1 day
Number of ensemble members	51

uncertainty into account when decision on preliminary release operation is made considering hydrological predictions because wrong estimation of future hydrological conditions can lead inappropriate decision making that may increase drought risk when conducting unnecessary preliminary release, or increase flood risk when not completing required preliminary release before a flood. It is therefore considered to be useful to consider ensemble hydrological predictions with temporal prediction range of around a week in the preliminary release operation of a reservoir.

## 2.2 Operational ensemble hydrological predictions provided in Japan

Ensemble prediction technique has been introduced into medium-term and long-term operational ensemble meteorological forecasts provided by Japan Meteorological Agency (JMA) in Japan. They include one-week forecast, one-month forecast, and seasonal forecast such as three-month and six-month forecasts. Among these ensemble forecasts, one-week ensemble forecast of precipitation, which is provided by One-week Ensemble Prediction System of JMA, is considered in this study because it can be considered useful to support decision making in preliminary release operation of a multi-purpose reservoir foreseeing hydrological conditions in the target river basin for the coming week. Specs of One-week Ensemble Forecast considered in this study is summarized as shown in Table 1. The forecasts provides prediction of accumulated precipitation for the coming 192 hours (i.e., eight days) with temporal resolution of six hours in a form of grid point values (GPVs) by 1.25° both in latitudinal and longitudinal horizons, and includes 51 ensemble members (prediction sequences).

Since One-week Ensemble Forecast of JMA was started in 2001, prediction data is not yet accumulated so much especially for flood cases. The prediction model also have experienced minor and major improvements since the operational prediction started, which may change the error structure of predictions provided by the model. These prevent comprehensive analyses on effects or impacts of prediction and its uncertainty on performance of reservoir operation, because a number of prediction

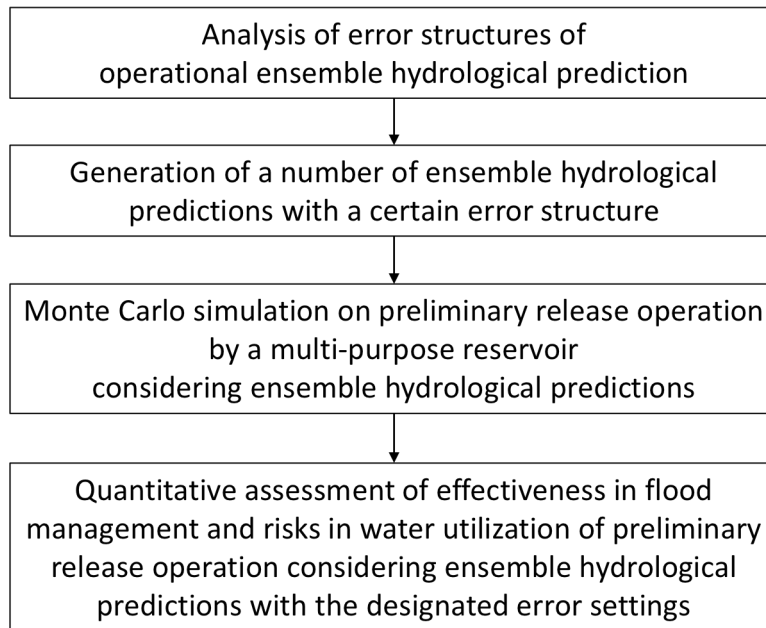


Figure 1: Framework of the proposed method to analyze effectiveness and risks of integrated reservoir operation considering ensemble hydrological prediction.

data provided by a prediction system with a same error structure is needed for such analyses on effects of prediction and its uncertainty. The challenge of scarcity of prediction data therefore needs to be overcome in order to conduct a comprehensive analysis on availability of ensemble hydrological predictions in reservoir operation.

### **2.3 Framework of assessment on effectiveness of preliminary release operation considering ensemble hydrological predictions**

The proposed framework to analyze effectiveness and impacts of preliminary release operation considering ensemble hydrological predictions is summarized as follows. Firstly, error structures of operational ensemble hydrological prediction is analyzed. Ensemble streamflow prediction derived from One-week Ensemble Forecast of precipitation provided by JMA is considered as an operational ensemble hydrological prediction in this study. Error structures of this ensemble streamflow prediction is analyzed considering typical prediction error indices such as error of ensemble mean prediction or spread of ensemble prediction. A number of ensemble streamflow predictions are then artificially generated by use of a simulated generation model of ensemble predictions considering those error structures in order to supplement scarce prediction data with a same error structure. Simulation of preliminary release operation of a multi-purpose reservoir is then conducted for test flood events considering each ensemble streamflow prediction generated in the previous process as a Monte Carlo simulation to analyze effectiveness and risks of preliminary release operation

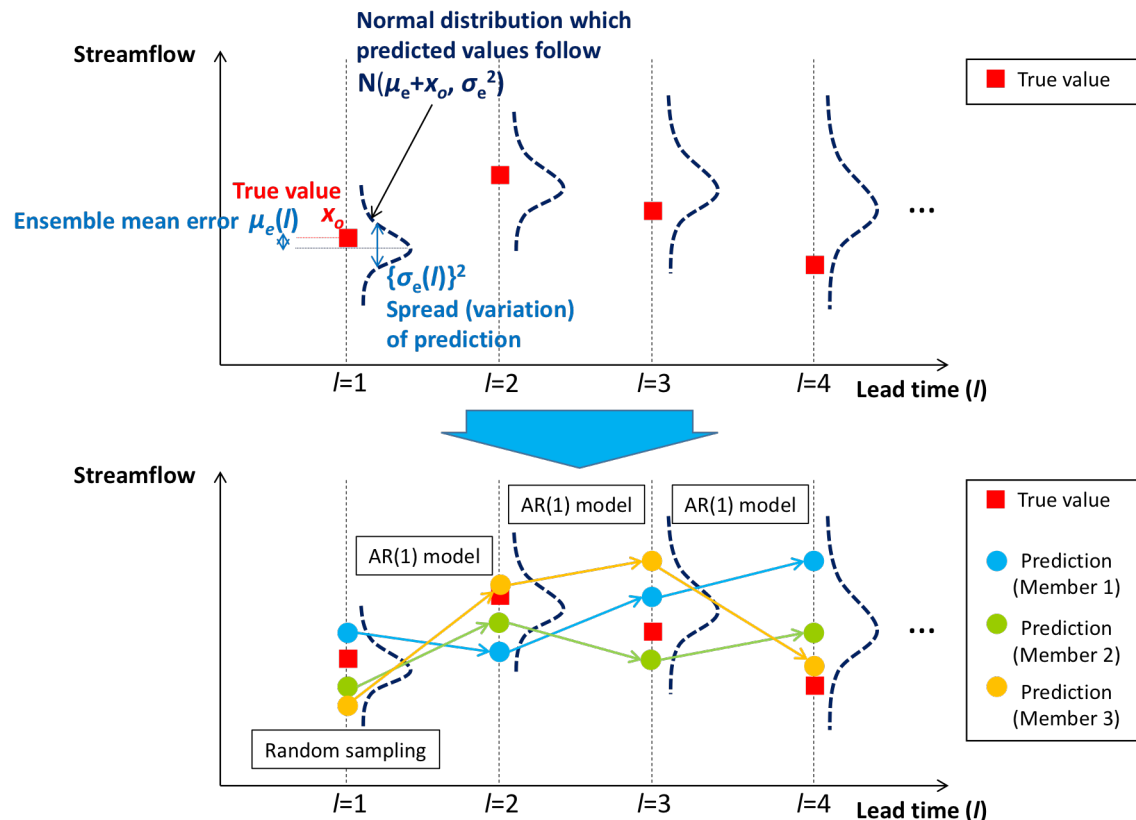


Figure 2: Synthetic generation of a series of ensemble streamflow prediction.

considering ensemble hydrological prediction with the estimated error structure. Probabilistic information on robustness of preliminary release operation or risks in water utilization can also be derived from the results of the Monte Carlo simulation by seeing the number of simulations where prior release operation is successfully completed before the flood event or the number of simulations where reservoir water storage is not recovered after the flood event, respectively. The flow diagram of the proposed framework is shown in Figure 1.

### 3. GENERATION OF ENSEMBLE STREAMFLOW PREDICTIONS

In order to supplement scarcity of actual prediction data, ensemble hydrological predictions with an error structure are synthetically generated in this study. River streamflow is considered as a hydrological variable to be predicted here. Synthetic generation of ensemble streamflow predictions is conducted according to the method proposed by Tokutsu *et al.* (2016).

In this method, a predicted value is generated by adding a value of prediction error synthetically generated to the true value of inflow in order to make it easy to simulate error structures of predictions. Values of prediction error are generated by randomly sampling values from a probabilistic distribution which prediction errors

follow. Various distributions can be assumed as a candidate for the probabilistic distribution of prediction error. One way to decide the probabilistic distribution of prediction error is to estimate its probabilistic distribution from prediction errors of actual ensemble predictions. Another simple way is to assume a simple probabilistic distribution which prediction errors follows. Those distribution may include a normal distribution or a lognormal distribution. Once the type of probabilistic distribution is assumed, one can derive parameters of the distribution such as the mean or the variance (if it is a normal distribution) from actual prediction data. In order to make the generation model of predictions as simple as possible to make it easy to assess the results while reflecting error characteristics of actual predictions, a normal distribution is assumed as the probability distribution which prediction errors follow, deciding the values for the mean and variance of the distribution based on actual prediction data in this study.

Values of prediction error are then generated by randomly sampling values from the assumed normal distribution. With this generation model, the mean and variance of the distribution for prediction error respectively correspond to error of ensemble mean and spread, which are two typical accuracy indices of ensemble predictions. Accuracy (or uncertainty) of ensemble predictions can therefore be controlled by changing the values for the mean and variance of the normal distribution assumed to be followed by prediction errors in this generation model.

The generation procedure of an ensemble streamflow prediction sequence can be described as follows (Figure 2). Firstly, a value is randomly sampled for the prediction error of an ensemble member for the next time step ( $l=1$ ). A series of prediction errors is then generated by use of a first-order autoregressive (AR(1)) model assuming that prediction errors have serial correlation. Supposing that the mean and the variance of the normal distribution which prediction errors follow are respectively a function of lead time, the AR(1) model for generation of a series of prediction errors can be described as follows (Takeuchi & Sivaarhithkul, 1995):

$$e(l, m) = e'(l, m) + m_e(l) \quad (1)$$

$$e'(l, m) = e'(l-1, m) \cdot \rho_L(1) \cdot \frac{\sigma_e(l)}{\sigma_e(l-1)} + w(l, m) \sqrt{1 - \{\rho_L(1)\}^2} \quad (2 \leq l \leq L) \quad (2)$$

where  $e(l, m)$  is prediction error of ensemble member  $m$  ( $m=1, \dots, M$ ) provided with lead time  $l$  ( $l=2, \dots, L$ ),  $\mu_e(l)$  and  $\sigma_e(l)$  are respectively the mean and standard deviation of the normal distribution followed by errors of prediction with lead time  $l$ ,  $\rho_L(1)$  is the

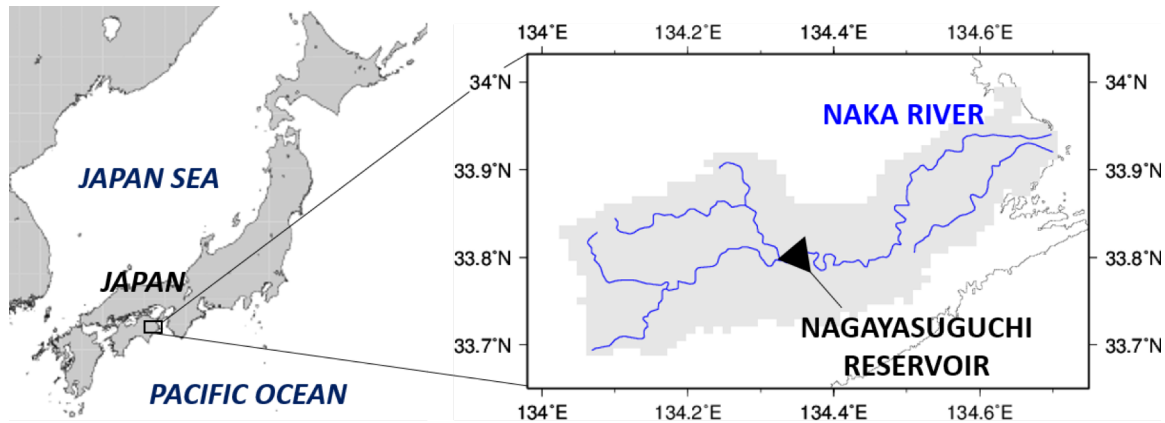


Figure 3: Location of the Naka River basin and the Nagayasuguchi Reservoir.

first order autocorrelation of errors of predictions provided for the successive lead time, and  $w(l,m)$  is white noise which follows  $N(0, \{\sigma_e(l)\}^2)$ . An ensemble streamflow prediction sequence can be generated by adding the true values of streamflow to the series of prediction errors generated by this method for each ensemble member for each predicted time step. Generally speaking, it is expected that spread of ensemble prediction becomes greater as lead time of prediction becomes longer. In order to incorporate this characteristics of ensemble predictions into the generation model, variance of prediction errors  $\{\sigma_e(l)\}^2$  can be defined as a function of lead time  $l$  as shown in the following equation.

$$\{\sigma_e(l)\}^2 = al + b \quad (l = 1, 2, \dots, L) \quad (3)$$

By using this equation, the degree of error growth (or uncertainty growth) of ensemble predictions can be changed. Although one can employ other functions such as exponential or quadratic functions to represent a rapid growth of prediction error along the lead time, the linear function defined by Equation (3) is employed in this study based on the result of analysis on error growth of operational hydrological predictions by Nohara & Hori (2017) and Tokutsu *et al.* (2016). One set of ensemble streamflow prediction can be generated through the process described above. Prediction is updated by generating a series of ensemble streamflow prediction, without considering correlation between errors of predictions before and after updated, assuming that characteristics of prediction errors do not remain after prediction update in this study.

## 4. CASE STUDY

### 4.1 Study area

The proposed method was applied to the Nagayasuguchi Reservoir in the Naka River



Table 2: Operational characteristics of the Nagayasuguchi Reservoir.

Items	Values
Active storage capacity (m <sup>3</sup> )	43,497,000
Water use capacity (m <sup>3</sup> )	43,497,000
Flood control capacity (m <sup>3</sup> )	10,960,000
Storage volume to be released by the first stage of preliminary release (m <sup>3</sup> )	5,397,000
Storage volume to be released by the second stage of preliminary release (m <sup>3</sup> )	10,960,000
Designed inflow to start flood control (m <sup>3</sup> /s)	2,500
Designed flood inflow (m <sup>3</sup> /s)	6,400
Designed release discharge for flood control (m <sup>3</sup> /s)	5,400
Maximum release discharge in case of non-flood situation (m <sup>3</sup> /s)	500

Basin, Japan (Figure 3). The Nagayasuguchi Reservoir is a multi-purpose reservoir which is operated for flood control, water supply and power generation. Operational characteristics of the Nagayasuguchi Reservoir are summarized as shown in Table 2. Because the Nagayasuguchi Reservoir and the Naka River basin locate in the southwest part of Japan where major floods and droughts occur frequently due to large variation in precipitation, preliminary release operation has been introduced into the Nagayasuguchi Reservoir to bring out the capacity of the reservoir for both flood and drought managements. The reservoir does not have seasonal restriction for its storage water level for preparation for flood control during the wet season, which is often seen in reservoirs in Japan. Instead, empty storage volume for flood control is secured only when flood occurrence is predicted by conducting preliminary release operation. The preliminary release operation of the Nagayasuguchi Reservoir consists of two steps: water storage level is decreased to the height of 222.7 m above the sea level (equivalent to 38.1 million cubic meter (MCM) in storage volume) by releasing water of 5.397 MCM as the first step of the preliminary release operation if rainfall is predicted after inflow of the reservoir exceeds 70 m<sup>3</sup>/s; and storage water level is decreased to the height of 219.7 m above the sea level (equivalent to 32.537 MCM in storage volume) by releasing water as the second step of the preliminary release operation if inflow of the reservoir exceeds 500 m<sup>3</sup>/s. By the two steps of the preliminary release operation, storage water of 10.96 MCM is released in order to secure empty volume as much as the flood control capacity. On the other hand, water amount to be released from the reservoir is calculated by the following equation during flood control operation after inflow exceeds 2,500 m<sup>3</sup>/s:

$$r_t = 0.774(i_t - 2500) + 2500 \quad (4)$$

where  $r_t$  and  $i_t$  are respectively water release and inflow at time step  $t$ .

#### 4.2 Analysis on error structures of operational ensemble hydrological prediction

Error structures of operational ensemble hydrological prediction was analyzed to decide the values for the mean and variance of the normal distribution for synthetic generation of prediction errors. Because inflow of the reservoir is the important variable for decision making on preliminary release operation of the Nagayasuguchi Reservoir, ensemble inflow prediction was estimated from the One-week Ensemble Forecast of precipitation of JMA.

Firstly, ensemble predictions of precipitation at rain gauges in the catchment of the reservoir were estimated from GPVs of the One-week Ensemble Forecast of precipitation. Multi-variable linear regression (MLR) models were respectively developed for prediction of precipitation at eight rain gauges in the catchment considering six GPVs of predicted precipitation as explaining variables. Ensemble inflow prediction was then estimated from ensemble precipitation predictions for the eight rain gauges by use of Hydro-BEAM (Hydrological River Basin Environment Assessment Model), a distributed rainfall-runoff model developed by Kojiri (2006). Equations and details of settings of Hydro-BEAM for the Nagayasuguchi Reservoir catchment is available in Nohara *et al.* (2015). Through this processes, ensemble inflow prediction for the coming 192 hours with time resolution of an hour was derived from GPVs of the JMA's One-week Ensemble Forecast of precipitation.

Error structures of ensemble inflow predictions were then analyzed with predicted and observed data for historical flood events occurred from 2006 to 2011. As a result of the analysis, the equations of the mean error and spread (variance) of ensemble inflow predictions at each lead time were respectively estimated as follows:

$$\mu_e(l) = -0.1346l - 136.4 \quad (l = 1, 2, \dots, L) \quad (5)$$

where  $L$  is identical to 192 (hours) in this case study. Because precipitation predictions derived from JMA's One-week Ensemble Forecasts generally had a tendency of underestimation for the region including the target river basin even after bias correction by the MLR models, mean error of inflow prediction was also negative for all lead times of prediction. On the other hand, spread (variance) values of ensemble inflow

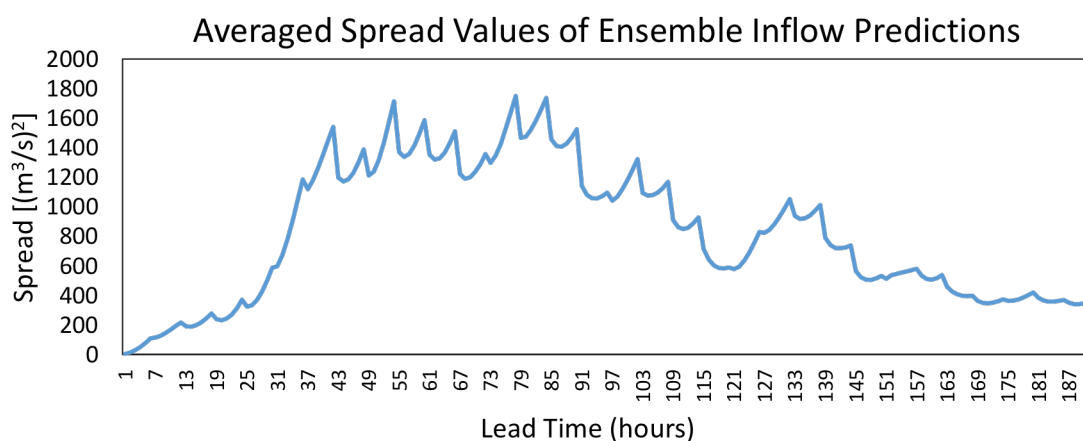


Figure 4: Spread values averaged over ensemble inflow predictions.

predictions for the Nagayasuguchi Reservoir did not show a simple relationship with lead time of the prediction as shown in Figure 4. The values of spread averaged over predictions increase as lead time becomes long until around three days ahead, while they gradually decrease as lead time becomes long after four days ahead. This characteristics in spread values is different from general tendency of ensemble meteorological or hydrological predictions where spread values grow as lead time becomes longer. The reason why spread values tend to decrease when lead time becomes long ahead can be considered because ensemble inflow predictions considered in this study did not foresee occurrence of a flood well with a long lead time and most ensemble members underestimated the situations with small predicted values which brought high convergence of ensemble members in those long lead times. As the estimated characteristics of averaged spread values were a bit complicated to represent relationships between spread and lead time with a simple function, the values shown in Figure 4 were respectively used as spread values for generation of ensemble inflow predictions for each lead time in the next process.

#### 4.3 Monte Carlo simulation of preliminary release operation

Generation of ensemble inflow predictions for the coming 192 hours (eight days, identical to the temporal range of JMA's One-week Ensemble Forecast) were then conducted deriving the mean and variance of prediction errors respectively from Eq. (5) and spread values shown in Figure 4. Serial correlation of prediction errors between successive lead times was assumed to be 0.9 based on the analysis conducted in Amai *et al.* (2014). A thousand series of ensemble inflow prediction were generated in this case study. Monte Carlo simulations of preliminary release operation of the Nagayasuguchi Reservoir were then conducted for 1,000 times by respectively

Table 3: Results of simulations on preliminary release operation (when ensemble mean predictions were considered).

Events	Rate of simulations where preliminary release conducted (%)	Rate of simulations where water storage recovered (%)	Mean storage rate after flood (%)
Flood 1	0.0	100.0	100.0
Flood 2	100.0	100.0	100.0

Table 4: Results of simulations on preliminary release operation (when the ensemble member with the maximum value of prediction was considered).

Events	Rate of simulations where preliminary release conducted (%)	Rate of simulations where water storage recovered (%)	Mean storage rate after flood (%)
Flood 1	99.7	96.7	99.9
Flood 2	100.0	100.0	100.0

considering a series of ensemble inflow prediction out of 1,000 predictions generated under the same parameters for prediction error. Two flood events were considered in this case study: a small flood event with the peak inflow rate of 535.0 m<sup>3</sup>/s which is slightly greater than the criteria to start preliminary release operation (denoted by Flood 1), and a large flood event with the peak inflow rate of 2049.3 m<sup>3</sup>/s which was much greater than the criteria to conduct preliminary release operation to the second stage according to the actual operation rule (denoted by Flood 2). On the other hand, two ways were considered to decide to conduct preliminary release operation considering ensemble inflow prediction. One is the way to decide to start preliminary release considering ensemble mean prediction, and the other is the way to consider the ensemble member which predicts the greatest value to decide to conduct preliminary release. In both ways, preliminary release operation was decided based on the maximal value included in the prediction sequence for the next 192 hours. A thousand simulations of preliminary release operation considering ensemble inflow prediction were conducted respectively for each flood event.

The results of the analysis based on the simulations of reservoir operation are summarized in Tables 3 and 4. It can be seen in Table 3 that preliminary release was not conducted properly in all simulations when ensemble mean predictions were considered while there is no failure in recovering water after either flood. The reason why preliminary release operation was not conducted because inflow greater than the criteria to conduct preliminary release operation to the second stage (500 m<sup>3</sup>/s) was not predicted well by ensemble inflow predictions. On the other hand, preliminary release operation was conducted successfully for both flood events in most

simulations when the ensemble member with the highest prediction was considered as shown in Table 4. Although a minor risk in water storage recovery can be a drawback, the operation method of preliminary release considering the ensemble member with the greatest prediction value can be the better way to decide to conduct preliminary release operation when ensemble inflow prediction has a tendency of underestimation as considered in this case study. Although more comprehensive case studies with more flood events are needed to derive an effective method to conduct preliminary release of a reservoir, the proposed framework to investigate effects of preliminary release operation can provide reservoir managers with quantitative information which enables to design the way to use ensemble hydrological predictions considering potential effects or risks both in flood and drought managements.

## 5. CONCLUSION

A Monte Carlo-based method to analyze effectiveness and risks of preliminary release operation of a multi-purpose reservoir for flood management considering real-time ensemble hydrological predictions was developed in this study. A generation model of ensemble inflow predictions was developed to synthetically generate multiple ensemble inflow prediction sequences with designed values of error mean and spread for the Monte Carlo simulations of preliminary release operation of a reservoir considering imperfect ensemble hydrological predictions. As a result of the case study on preliminary release operation considering ensemble inflow predictions with a tendency of underestimation that was derived from operational ensemble forecast, the operation method of preliminary release considering the ensemble member with the greatest prediction value can be considered to be a reliable way to decide to conduct preliminary release operation without failure in flood management while there is a minor risk in water recovery after the flood. Although a comprehensive analysis employing more flood events are needed to derive an effective method to conduct preliminary release of a reservoir, the proposed framework to investigate effects of preliminary release operation can be considered to be able to provide reservoir managers with quantitative information which enables to design the way to use ensemble hydrological predictions considering potential effects or risks both in flood and drought managements.

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