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Decision Support For Flood Control Operation Of A Multi-Purpose Reservoir Considering Operational One-Week Ensemble Forecast Of Precipitation

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DECISION SUPPORT FOR FLOOD CONTROL OPERATION OF A MULTI-PURPOSE RESERVOIR CONSIDERING OPERATIONAL ONE-WEEK ENSEMBLE FORECAST OF PRECIPITATION

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A method of decision support for reservoir's flood control operation including preliminary release considering an operational weekly ensemble precipitation prediction is discussed in this paper. Ensemble streamflow predictions are calculated from One-week Ensemble Forecast of precipitation provided by Japan Meteorological Agency by use of a distributed rainfall-runoff model. The future states of the target reservoir such as storages and water releases are estimated in form of ensemble prediction through the simulation of reservoir operation based on actual operation rules considering the ensemble streamflow prediction. Consequences of expected operations of the reservoir in both of the flood control during the flood event and recovery in storage water after the event can be assessed considering such estimation. The proposed method was applied to Nagayasuguchi Reservoir in the Naka River basin, Japan, demonstrating capability of the approach to support decision making in preliminary release operation of reservoirs.

INTRODUCTION

Ensemble hydro-meteorological predictions, which generate multiple numerical predictions with different initial conditions, are expected to provide information not only on future hydrological and meteorological conditions but also on uncertainty contained in the predictions. Using such information is considered to be effective for more robust decision making in reservoir operations in which all the possible scenarios and their consequences in flood management or water utilization must be taken into account. From the point of view, many studies have been conducted to introduce ensemble hydro-meteorological predictions into reservoir operations in recent years. Faber and Stedinger [1] proposed three dynamic programming (DP) models for optimization of reservoir operation for drought management with weekly updated forecast information derived from operational ensemble streamflow prediction (ESP). Nohara and Hori [2] developed a stochastic dynamic programming (SDP) model to optimize water release from the target reservoir for real-time operation for drought management considering two operational ensemble forecasts: one-month and one-week ensemble precipitation predictions provided by Japan Meteorological Agency (JMA). These studies mainly focus on long-term reservoir operation for water utilization. On the other hand, studies have been conducted to effectively introduce ensemble hydro-meteorological predictions to short-term reservoir operation for flood management. For instance, Masuda and Oishi [3] investigated integrated flood control operation of a multi-reservoir system in the Nabari River basin considering JMA's One-week Ensemble Forecast of precipitation.

However, the number of studies introducing ensemble hydro-meteorological predictions to short-term reservoir operation for flood management still remains small compared to those introducing to long-term operations for water utilization. Further studies are needed for more effective introduction of ensemble hydro-meteorological predictions to short-term reservoir operation.

In this paper, a method to support decision making in reservoir operation for flood control considering One-week Ensemble Forecast of precipitation provided by JMA is discussed. Preliminary release operation, which releases stored water from a reservoir precedential to arrival of floods and is employed for multi-purpose reservoirs in Japan, is focused on as a flood control operation by a reservoir. ESPs for a coming week are calculated form JMA's One-week Ensemble Forecasts of precipitation by use of the Hydrological River Basin Environment Assessment Model (Hydro-BEAM), a distributed rainfall-runoff model. Ensemble estimations of the target reservoir's states such as storage volumes or releases are then calculated from the ESPs through simulation of flood control operation according to actual operation rules of the reservoir in order to provide supporting information by showing possible trajectories of reservoir's states in the future. A way to support decision making in preliminary release operation is then discussed considering the estimated future states of the target reservoir.

OUTLINE

Preliminary release operation of a multi-purpose reservoir

Preliminary release operation is a way of flood management by a reservoir effectively using its limited storage capacity. In the preliminary release operation, storage water is released from the reservoir in advance of floods' arrival by considering hydrological forecasts so as to secure enough empty storage volume to control the flood by storing water with the volume during the flood. This operation enables the reservoir to decrease its storage level to the extent required for flood control during flood events while the reservoir can keep storage water level as high as possible for water utilization under non-flood situation. After inflow to the reservoir diminishes, the storage needs to be recovered to a designated level to be secured for water utilization. While preliminary release operation is considered to be an effective way of managing floods, the operation may cause a negative impact for both flood management and water utilization because preliminary release operation of reservoirs largely depends on real-time hydrological predictions which have some uncertainty in nature. If a flood is overestimated, the storage water of the reservoir may be released more than necessary and that may cause shortage in water storage after the flood. On the other hand, if a flood is underestimated, enough empty storage for flood management may not be secured in advance of the flood's arrival and that may cause overflow at the reservoir as well as downstream. Careful consideration of uncertainty in hydrological predictions is therefore important when a decision is made for preliminary release.

Specifications of the one-week ensemble precipitation forecast considered in this study

Ensemble hydro-meteorological forecasts, which generate multiple numerical predictions with different initial conditions, have been developed in many regions. In Japan, JMA provides several ensemble forecasts on medium-term and long-term meteorological conditions. They include one-week forecast, one-month forecast and three-month forecast. As this study focuses on reservoir's flood control operation and a flood event generally lasts for several days in Japan One-week Ensemble Forecast of precipitation provided by JMA is considered in this study. The basic specification of the forecast is shown in Table 1.

METHODOLOGY

Estimation of ensemble precipitation predictions at the target river basin

JMA's One-week Ensemble Forecast provides ensemble precipitation prediction (EPP) for the coming eight days in the form of grid point values (GPVs). Because these GPVs do not consider the topographical effects and the interval of grid points is not small enough to describe spatial

Table 1. Basic specification of One-week Ensemble Forecast provided by JMA

Latitude range	Longitude range	Spatial resolution	Temporal range	Temporal resolution	Update frequency	Number of members
22.5ºN~71.25ºN	90ºE~90ºE	1.25°	192 hours*	6 hours	1 day**	51**

*The temporal range has been extended to 264 hours since March in 2013.

**Update frequency and number of members have also been changed since February 2014.

distribution of precipitation, a correction of forecasted GPVs is needed to estimate precipitation for the target basin. In this study, a multiple linear regression model (MLR model) is used to estimate EPPs in the target basin. The equation of the MLR model is described as follows:

$$P = a_0 + \sum_{i=1}^{I} a_i x_i \tag{1}$$

where P = hourly basin precipitation, a_0 = the intercept, i = considered grid point, I = the total number of considered grid points, a_i = the regression coefficient for explaining variable x_i, and x_i = GPV of hourly precipitation at grid point i as an explaining variable. The estimation of basin precipitation is respectively conducted from each ensemble member of GPVs of precipitation.

Estimation of ensemble stream-flow predictions

In order to estimate ESPs in the target river basin from EPPs, Hydro-BEAM is used in this study. The Hydro-BEAM is a distributed rainfall-runoff model which was first developed by Kojiri [4]. In Hydro-BEAM, a river basin is modeled as a uniform array of mesh cells. Each mesh cell is one kilometer square and is summarized into river mesh cell and non-river mesh cell. Each non-river mesh cell consists of one river and two slopes interposing the river, and each slope has the structure of three soil layers named the layers A, B and C from the top. Rainfall onto each mesh cell is estimated from the precipitation at gauges in the target river basin by use of Inverse Distance Weighted model (IDW model). The equation of IDW model is described as follows:

$$W_h = \frac{\sum_{j=1}^{J} \frac{\kappa_j}{L_j^2}}{\sum_{j=1}^{J} \frac{1}{L_j^2}} \tag{2}$$

where W_h = precipitation at mesh h, κ_j = precipitation observed at station j in the target basin, L_j = distance between mesh h and station j, J = the total number of rainfall stations in the basin.

Rainfalls onto non-river mesh cells, which are not represented as river channels, are calculated in the slopes of the mesh cells. On the surface and in the layer A, surface and subsurface flows are considered and calculated by using a kinematic wave model as shown in the following equations (see also Sato *et al.* [5]). And five land uses (field, forest, urban area, paddy field and water body) are considered and reflected in the equations.

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = f\gamma, \tag{3}$$

$$q = \begin{Bmatrix} \alpha(h-d)^{\frac{5}{3}} + ah \\ ah \end{Bmatrix}, when \begin{Bmatrix} h \geq d \\ h < d \end{Bmatrix} \tag{4}$$

$$d = D\lambda, \qquad \alpha = \frac{\sqrt{\sin\theta}}{n}, \qquad a = \frac{k \sin\theta}{\lambda}, \ \gamma = FR \tag{5}$$

where h = water level (m), q= discharge per unit depth ($m^{-3}s^{-1}$), f = direct runoff rate, γ = effective rainfall intensity (ms^{-1}), d = saturated water storage level (m), D = the thickness of the layer A, sin θ = the gradient of slope, n = Manning's roughness coefficient ($m^{-1/3}s$), k = a coefficient of permeability (ms^{-1}) and λ = effective porosity. The values for direct runoff rate f and Manning's roughness coefficient n are also decided considering each land use, respectively.

In the layers B and C, water flow is calculated by a liner storage function model described as the following equations:

$$\frac{\partial S_B}{\partial t} = I_B - O_B, \quad O_B = (k_1 + k_2)\mathrm{S_B}, \quad I_B = (1-f)\gamma \tag{6}$$

$$\frac{\partial S_C}{\partial t} = I_C - O_C, \quad O_C = k_3\mathrm{S_C}, \quad I_C = k_1 S_C \tag{7}$$

where S_B = depths of the layer B (m), I_B = runoff inputs to the layer B(m^3s^{-1}), O_B = runoff output to the river channel (m^3s^{-1}), k_1 = the horizontal runoff coefficients of the layer B (s^{-1}), k_2 = the vertical runoff coefficients of the layer B (s^{-1}), S_C = depths of the layer C (m), I_C = runoff inputs to the layer C(m^3s^{-1}), O_C = runoff output to the river channel of adjacent mesh cells(m^3s^{-1}), k_3 = the horizontal runoff coefficient in the layer C (s^{-1}), respectively. Vertical infiltration from the layer C is not considered in this study.

At river mesh cells, the flow is calculated by a kinematic wave model for an open channel assuming that its cross-sectional shape is triangular. The equations are defined as follows:

$$\frac{\partial E}{\partial t} + \frac{\partial Q}{\partial x} = q_r, \qquad Q = \alpha_r A^g, \qquad g = \frac{4}{3} \tag{8}$$

$$\beta = \left(\frac{\sqrt{I_r}}{n}\right)\left(\frac{u}{\left(2\sqrt{1+u}\right)^2}\right)^{\frac{1}{3}}, u = \frac{B}{H} \tag{9}$$

where E = discharge section area (m^2), Q = discharge (m^3s^{-1}), q_r = lateral inflow discharge (m^3s^{-1}), α_r = the constant of Manning's equation, I_r = the channel slope, B = the channel width (m) and H = maximal water depth (m) which is expected when the design flood occurs. Discharged water from each mesh is assumed to flow to the mesh cell whose elevation is the lowest in the four adjacent mesh cells.

Estimation of reservoir states and decision support for preliminary release operation

The target reservoir's future states are estimated in form of ensemble predictions from the ESPs calculated in the previous process. Storages and water releases for the coming eight days are estimated from each member of ESPs through a simulation of flood control including preliminary release according to the actual operation rules of the target reservoir. Each estimated trajectory of the water releases is considered to have possibility to be conducted. By use of ensemble inflow predictions (EIPs), multiple trajectories of water storages expected as consequences of each water release policy are estimated. The variation and probability of the expected water storage can also be estimated by evaluating the set of trajectories of water storage. As preliminary release operation is considered in this study, information on securing enough empty storage for flood control and recovering the water storage volume after flood events are mainly provided.

CASE STUDY

Study area

The proposed method was applied to Nagayasuguchi Reservoir located in Naka River basin in Japan. Nagayasuguchi Reservoir is a multi-purpose reservoir for flood control, water supply and power generation. The specification of Nagayasuguchi Reservoir is shown in Table 2. The reservoir does not have any restriction of water storage level for flood control under non-flood situation. When occurrence of a flood is predicted, the reservoir conducts preliminary release operation to secure enough empty storage volume by decreasing water storage level so that flood control can be safely conducted with the empty volume. The preliminary release operation of Nagayasuguchi Reservoir consists of two steps. The first step is that if rainfall is predicted under the situation that inflow to the reservoir exceeds 70m^3/s, the storage volume should be decreased to 38,100,000 m^3 by releasing water. The second step is that if inflow to the reservoir is expected to exceed 500 m^3/s, the storage volume is decreased to 32,537,000 m^3 by releasing water. If inflow exceeds 2,500 m^3/s which is the amount that the reservoir starts flood control operation, flood control operation is conducted by releasing water calculated by the following equation:

$$r_t = 0.774(i_t - 2500) + 2500 \tag{10}$$

where r_t and i_t are respectively water release (m^3s^{-1}) and inflow (m^3s^{-1}) at time step t.

Table 2. Specification of Nagayasuguchi Reservoir in Japan

Active storage capacity (m^3)	43,497,000
Water use capacity (for power generation and water supply) (m3)	43,497,000
Flood control capacity (m^3)	10,960,000
Water storage volume after first step of preliminary release (m3)	38,100,000
Water storage volume after second step ofpreliminary release (m3)	32,537,000
Designed inflow to start flood control operation (m^3/s)	2,500
Designed flood inflow (m^3/s)	6,400
Designed release discharge for flood control (m^3/s)	5,400
Maximal release discharge in case of non-flood situation (m^3/s)	500

Development of models for the study area

In order to estimate EPPs in the target river basin, a MLR model was developed employing historical data of precipitation in wet season (from May to October) since 2006 to 2009. Precipitations observed at seven gauges in the catchment of Nagayasuguchi Reservoir were considered as objective variables, and a MLR model was respectively developed to estimate precipitations at every precipitation gauge. Ensemble mean predictions of precipitation forecasted by JMA's One-week Ensemble Forecast for the six grid points around the catchment of Nagayasuguchi Reservoir were considered to be candidates of explaining variables of the regression models. As the result of comparison in the deterministic coefficients, the forecasted precipitation for the grid point (33.75°N, 133.75°E) which is nearest the target catchment was chosen as the explaining variable of the MLR models for prediction of precipitation at every precipitation gauge. As for the rainfall-runoff process, parameters of Hydro-BEAM were adjusted so as to maximize reproducibility in streamflows in 12 flood events observed from 2009 to 2011.

Results and discussions

The proposed method was applied to flood events in the Naka River basin in 2012. Results for two flood events, which respectively occurred on July 11th, 2012 (denoted by Event 1) and September 30th, 2012 (denoted by Event 2), are shown here as examples. Results of the EIP calculated for Events 1 and 2 by using Hydro-BEAM from JMA's One-week Ensemble Forecast of precipitation are shown in Figures 1 and 2, respectively. The EIPs tended to underestimate the real situation in most events like Event 1 shown in Figure 1, where all ensemble members were smaller than observed inflow. One-week Ensemble Forecast of had tendency of underestimation for the grid points considered in this case study, and the tendency could not completely corrected even a bias correction process by MLR models was considered. However, some members of EIPs foresaw the peak inflow in a few flood events like Event 2 shown in Figure 2.

From the EIPs estimated in the previous process, water release policy was estimated for each ensemble member of inflow prediction. Through this process, 51 water release policies were obtained in total. The estimated 51 water releases policies of the target reservoir are summarized into three policies: conducting no preliminary release operation (denoted by Policy 1), conducting only the first step of preliminary release operation (denoted by Policy 2) and conducting the second step of preliminary release operation (denoted by Policy 3). The numbers of ensemble inflow members with which each water releases policy is chosen according to the actual reservoir operation rules in Event 1 and Event 2 are shown in Table 3.

When considering Policies 1 and 2, the impacts of Policy 1 and 2 on flood management need to be assessed as the target reservoir does not secure the maximum empty storage volume for flood control designated in actual operation rule of the target reservoir. However, for Event 1 and Event 2, all members of EIPs did not exceed 2500m^3/s, which is the inflow amount that the target reservoir has to start flood control operation using empty storage volume. Thus, shortage in empty storage could not be evaluated as an impact on flood management. Instead, the number of

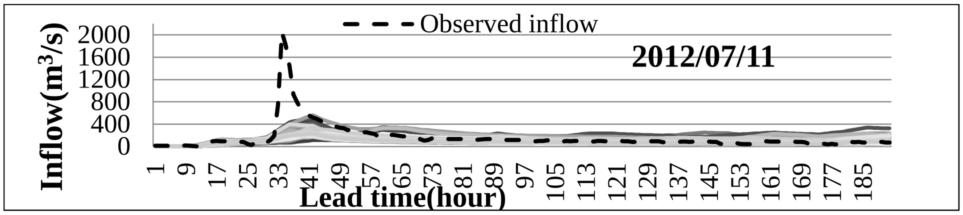

Figure 1. The result of EIP based on the forecast provided on July 10th, 2012 (Event 1)

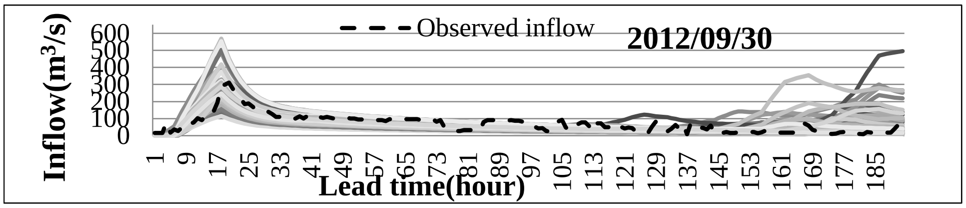

Figure 2. The result of EIP based on the forecast provided on September 29th, 2012 (Event 2)

Table 3. Number of members of EIPs for each water release policy

	Date of flood event	Policy 1	Policy 2	Policy 3
Number of members	2012/7/11 (Event 1)	12	37	2
	2012/9/30 (Event 2)	0	48	3

Table 4. The number of members in which the secured empty storage volume was smaller than the volume described in actual operation rule of the reservoir

flood event	Policy 1	Policy 2
2012/07/11 (Event 1)	39	2
2012/09/30 (Event 2)	51	3

ensemble scenarios of water storage state in which reservoir could not secure the empty storage volume designated by the actual operation rules was calculated as an assessment of the two water release policies on flood management.

Assuming that expected occurrence probability of each ensemble member was equal, the probability of securing designated empty storage for flood control could be estimated from the number of members. The results are summarized in Table 4. In Table 4, designated empty storage volume for flood control was expected not to be secured for the majority member of EIPs if Policy 1 is implemented. On the other hand, in case of Policy 2, the designated empty storage was expected to be secured for over 90% of ensemble members. A few ensemble members, however, suggested the necessity of second step of preliminary release operation.

When considering preliminary release operation (Policies 2 and 3), not only shortage in empty storage volume for flood control but also recovery of water storage after the flood event needs to be evaluated. Examples of estimated trajectories of water release in Policies 2 and 3 are respectively shown in Figures 3 through 6 with the water storages which were expected as consequences of the policies for Event 1 and Event 2. For each water release policy shown in Figures 3 through 6, the trajectories of storage volume had larger variation with the elapse of time.

In order to evaluate the degree of recovery in water storage volume after each flood event, the number of ensemble members of storage volume trajectories in which excessive stored water was released more than the volume designated in actual operation rule were calculated. The number of trajectories of water storage volume in which water storage recovered to 43,497,000 m^3 after flood event was also calculated, and averaged maximum volume of each trajectories of water storages after preliminary release operation was also calculated. The results are summarized in Table 5. In the case of Policy 3, for both Events 1 and 2, too much empty storage

Table 5. Results of estimation of effects of preliminary release operation on water utilization

Date of flood event	Water release policy	Number of members with which too much water was released	Number of members in which storage was recovered to the full capacity	Averaged maximum volume of water storage trajectories after flood (m^3)
2012/07/11 (Event 1)	Policy 2	12	42	42,800,000
	Policy 3	49	12	39,900,000
2012/09/30 (Event 2)	Policy 2	0	9	42,100,000
	Policy 3	48	0	36,700,000

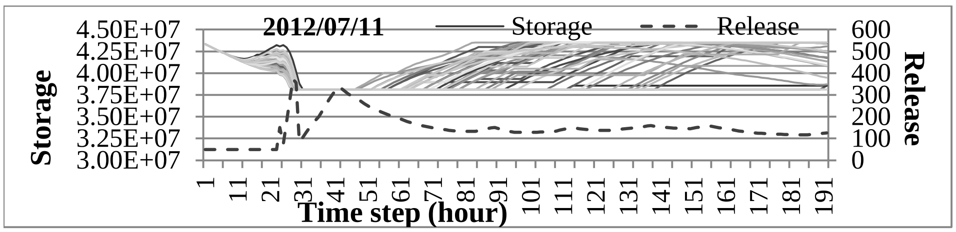

Figure 3. An example of release policy according to Policy 2 and the expected trajectories of water storage volume based on the forecast provided on July 10th, 2012 (Event 1)

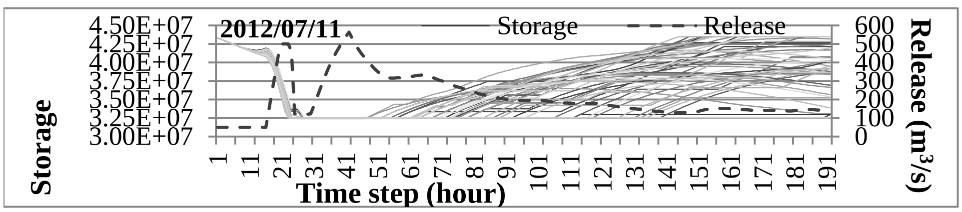

Figure 4. An example of release policy according to Policy 3 and the expected trajectories of water storage volume based on the forecast provided on July 10th, 2012 (Event 1)

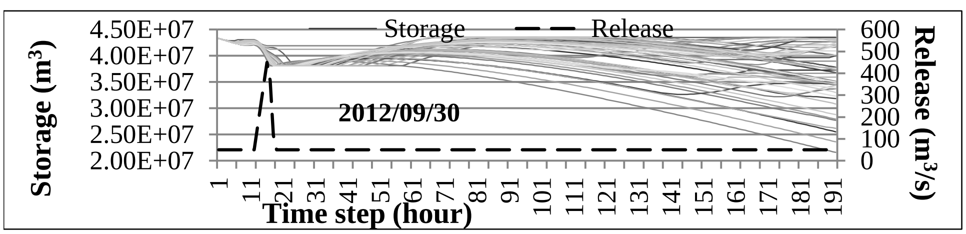

Figure 5. An example of release policy according to Policy 2 and the expected trajectories of water storage volume based on the forecast provided on September 29th, 2012 (Event 2)

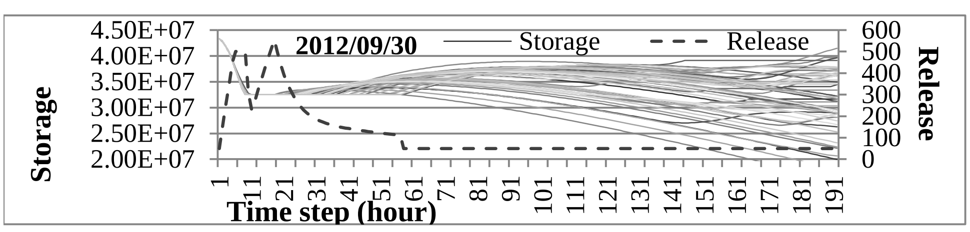

Figure 6. An example of release policy according to Policy 3 and the expected trajectories of water storage volume based on the forecast provided on September 29th, 2012 (Event 2)

was secured by unnecessary preliminary release, and water storage were expected not to recover after the floods for most members of EIPs. On the other hand, large number of storage trajectories showed recovery of the storage to the designated volume (43,497,000 m^3) when reservoir operation was conducted according to Policy 2. In this case, the averages of maximum water storage after preliminary release operation were greater than that in Policy 3, and the expected losses of water storage caused by preliminary release operation were considered to be small.

By using ensemble hydrological predictions, information on estimated reservoir conditions can be provided for reservoir managers in advance of flood's arrival as shown above. Information on effects of expected water release policies on both the flood control and water utilization can especially be considered useful for decision makings in the preliminary release operation of reservoirs. The probability and the variation of the effects are also considered to be valid information. However, ensemble inflow prediction tends to underestimate most flood situations because JMA's One-week Ensemble Forecast of precipitation has tendency of underestimation in this case study. The one of remained issue is to improve the accuracy of the precipitation prediction estimated by JMA's One-week Ensemble Forecast of precipitation. As this study described only the way of providing information to support reservoir managers, further investigation is considered necessary to improve a practical way of decision making for preliminary release operation considering operational ensemble hydrological predictions.

CONCLUSION

A method of decision support for flood control operation including preliminary release operation considering One-week Ensemble Forecast of precipitation provided by JMA was discussed. By considering the forecast, the expected water release policies and those effects on water utilization and flood management could be calculated and evaluated. Providing such information for reservoir managers is considered to be effective, especially in the scene that preliminary release operation, which may affect both water utilization and flood management, is expected to be conducted. It is, however, considered as an issue to improve the bias correction or downscaling method of One-week Ensemble Forecast GPVs provided by JMA in order to provide further effective information. It is also a remained issue to develop a practical way to make improved decisions in flood control operation including preliminary release operation considering operational hydrological ensemble predictions.

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