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REAL-TIME RESERVOIR OPERATION FOR DROUGHT MANAGEMENT CONSIDERING ENSEMBLE STREAMFLOW PREDICTIONS DERIVED FROM OPERATIONAL ENSEMBLE FORECAST OF PRECIPITATION IN JAPAN

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A real-time reservoir operation method for drought management with consideration of operational ensemble hydrological predictions is discussed in this paper. One-week and One month Ensemble Forecasts of precipitation provided by Japan Meteorological Agency are considered to estimate future hydrological conditions in a target river basin in the real-time reservoir operation for water supply. Ensemble streamflow prediction for the coming one month is estimated from the ensemble forecasts of precipitation by use of Hydro-BEAM, a distributed rainfall-runoff model. Reservoir operation is then optimized by stochastic dynamic programming considering the ensemble streamflow prediction estimated for the coming one month. Reservoir operation is conducted according to the water release policy optimized by the previous process. The proposed method was applied to Sameura Reservoir in the Yoshino River in Japan, demonstrating effectiveness of introducing the ensemble hydrological predictions in the drought management by a reservoir.

INTRODUCTION

Reservoirs play a significant role in drought management by stabilizing water supply with stored water. Effective consideration of real-time hydro-meteorological predictions is considered important as it can improve reservoir operation for drought management by enabling reservoir managers to design a strategy to operate the reservoirs based on the expected conditions in their target river basins provided by the predictions. However, establishing the effective way of reservoir operation considering real-time hydro-meteorological predictions is still challenging in the drought management where reservoir managers need to consider long-term hydro-meteorological predictions to estimate situations of the target basin in the long future. Hydro-meteorological predictions with longer lead time generally contain greater degree of uncertainty that makes decision makings more difficult in the reservoir operation.

As a countermeasure against increase in uncertainty contained in long-term predictions as mentioned above, ensemble hydro-meteorological predictions, which generate a set of predictions with different initial conditions to handle the growth of uncertainty in the predictions, have been developed in many regions in recent years. Ensemble hydro-meteorological predictions provide not only tendency of future hydrological conditions in the target basin but also possible future scenarios and degrees of certainty of the prediction, which may be useful for more robust decision makings in the reservoir operation for drought management. However, it is not yet very common for actual reservoir operation to quantitatively consider information on the possible scenarios or degrees of certainty of the prediction included by those predictions, because it requires handling complex data contained in the ensemble predictions that is often difficult for reservoir managers. A method to adequately consider such rich information provided by ensemble hydro-meteorological predictions needs to be investigated for enhanced decision makings in the reservoir operation for drought management.

From this point of view, studies have been conducted aiming to develop a method to effectively introduce ensemble hydro-meteorological predictions into the actual mid-term or long-term reservoir management. Faber and Stedinger [1] developed optimization methods for an actual reservoir system combining weekly updated forecast information from ensemble streamflow prediction (ESP) of the United States National Weather Service. They employed sampling stochastic dynamic programming (SSDP), which is one of the stochastic dynamic programming (SDP) approaches expanded to consider persistence in each scenario of ensemble predictions, for the method to optimize long-term water release by reservoirs in real time. Kim *et al*. [2] also developed an optimizing model to decide operational policies of a multi-reservoir system in the Republic of Korea by use of SSDP with monthly updated ESP. Nohara *et al*. [3] investigated optimizing processes of reservoir operation by three dynamic programming (DP) models including SDP and SSDP with operational one-month ensemble forecast of precipitation provided by Japan Meteorological Agency (JMA) for drought management. Alemu *et al*. [4] investigated value of ESPs by developing a decision support system (DSS) for optimization of reservoir operation for hydropower generation considering ESPs. These studies have demonstrated potential effectiveness of introducing even a single source of ensemble hydrological prediction to long-term reservoir operations.

On the other hand, more than one source of operational ensemble hydro-meteorological prediction is available in some region as meteorological or hydrological authorities provide hydro-meteorological forecasts with different ranges. JMA also provides several operational ensemble forecasts with different spatial and temporal properties in Japan, so that users can choose a prediction to consider according to spatial and temporal resolutions or ranges required for their decision makings. Consideration of multiple operational ensemble hydro-meteorological forecasts can be considered to enhance reservoir operation efficiency.

The paper describes a method for real-time reservoir operation for drought management considering two operational ensemble forecasts of precipitation as a fundamental study to introduce multiple ensemble hydrological predictions to drought management with effective combination. One-week and One-month Ensemble Forecasts of precipitation provided by JMA are considered in this study. Ensemble streamflow predictions for a target river basin are then estimated from the ensemble precipitation predictions by use of the Hydro-BEAM, a distributed rainfall-runoff model for the coming one month. Reservoir operation is then decided and conducted for drought management considering the estimated ensemble streamflow prediction for the coming month.

OUTLINE

Operational ensemble hydro-meteorological forecasts in Japan

JMA provides several operational ensemble weather forecasts which predicts mid-and long-term meteorological and hydrological conditions with their ensemble prediction system. They

Table 1. Key specs of JMA's One-month Ensemble Forecast and One-week Ensemble Forecast considered in this study

Ensemble forecast	Temporal range (days)	Temporal resolution	Spatial coverage	Spatial resolution (degrees)	Update frequency (day)	Number of members
One-month (JMA-EPS1)	33	1 day	Global	2.5	7	50
One-week (JMA-EPSW)	8*	6 hours	Japan Area (22.5°N-71.25°N, 90°E-180°E)	1.25	1†	51†

* Temporal range has been extended to 264 hours (11 days) since Mar. 28, 2013.
† Update frequency and the number of ensemble members included in each forecast have been respectively changed to twice a day and 27 since Feb. 26, 2014.

are designed to constitute a set of predictions for the coming three months, consisting of Warm/Cold Season Forecast (with six month range), Three-months Forecast, One-month Forecast and One-week Forecast, from the longest to the shortest in their ranges of prediction. Individual ensemble members, which provide possible scenarios of the future meteorological and hydrological conditions, are also available for these forecasts. In this study, ensemble precipitation predictions (EPPs) of JMA's One-month Ensemble Forecast (denoted by JMA-EPS1) and One-week Ensemble Forecast (denoted by JMA-EPSW), both of whose historical data are provided and available at the database operated by the GFD Dennou Club [5], are considered as medium- and long-term operational ensemble forecasts. The specs of the two forecasts are summarized as shown in Table 1.

Framework of reservoir operation considering two operational ensemble forecasts

Real-time reservoir operation for drought management is conducted considering two operational ensemble forecasts of precipitation updated day by day in the proposed method. Firstly, the EPP for the target river basin for the coming one month is estimated from JMA-EPS1 and JMA-EPSW considering temporal ranges and updating frequencies of the forecasts. EPPs for the coming eight days with 51 ensemble members are estimated from JMA-EPSW, and updated every day. On the other hand, the EPP after the coming nine days is estimated from JMA-EPS1, whose temporal range is 33 days, with 50 ensemble members, and updated every seven days. The schematic diagram of relationships between EPPs derived from JMA-EPS1 and JMA-EPSW is described as shown in Figure 1. EPPs for the target basin are estimated by use of linear regression equations, which are developed with historical data in Nohara and Hori [6] so as to represent relationships between basin precipitation and forecasted values for grid points near the target basin by JMA-EPS1 and JMA-EPSW, respectively.

ESP for the coming one month (max. 33 days) is then calculated from the EPP by use of the Hydrological River Basin Environment Assessment Model (Hydro-BEAM) [7], a distributed rainfall-runoff model. The model can calculate the amount of runoff water of every mesh in the target river basin, which enables to estimate the amount of runoffs at important points for drought management such as reservoir inflow or streamflow at a designated assessed point downstream the reservoir. The key theories and equations of the Hydro-BEAM are described in the following chapter. ESP for the coming one month, which consists of ESP with 51 members for the coming eight days and one with 50 members for the period from the nine days ahead to one month ahead (max. 33 days), can be estimated through this process. Water

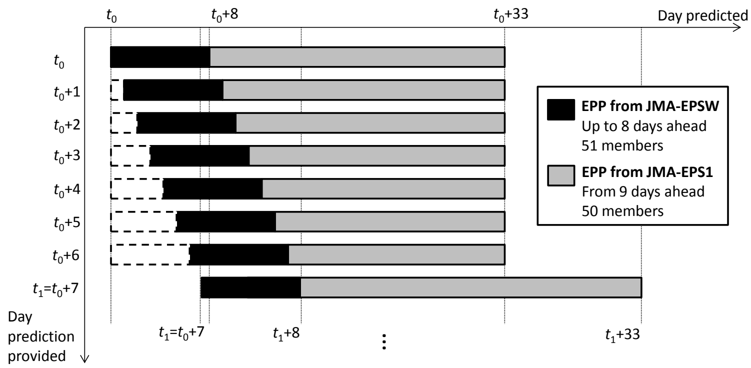

Figure 1. Schematic diagram of integration of EPPs derived from JMA-EPS1 and JMA-EPSW

release strategy of the target reservoir is then optimized so as to minimize drought damage for the coming one month considering the ESPs estimated in the previous process. Stochastic dynamic programming (SDP) is employed for the optimization algorithm considering stochastic nature of ESPs. Reservoir operation for water supply is conducted on a daily basis according to the estimated water release strategy, which is recalculated every day based on the updated ESPs derived from the newest JMA-EPS1 and JMA-EPSW.

RAINFALL-RUNOFF MODEL

ESPs are estimated for the coming one month from the EPPs for the target basin derived from JMA-EPS1 and JMA-EPSW by use of Hydro-BEAM in this study. The Hydro-BEAM is a cell concentrated type distributed rainfall-runoff model developed by Kojiri et al. [8]. The model divides each square-shaped grid cell into a pair of rectangular hill slopes and one river channel. The soil of each grid cell is represented as multi-layers including the upper soil (denoted by the layer A) and the two lower ones (denoted by the layers B and C). Runoff flow is assumed to be surface flow in the layer A, while a multi-layer linear storage function model is assumed to calculate base flows in the layers B and C. On the other hand, surface flow and sub surface flow are calculated by a kinematic wave model. Flow directions are decided based on digital elevation data so that water flows from the higher grid cell to the lower grid cell. Each grid cell is also divided into a river grid cell and non-river one, and five land uses (namely, forest, field, urban area, paddy field and water body) are considered for land surface and the layer A of a non-river grid cell so that different parameters for soil and flow can be employed based on the land use. For a river grid cell, streamflow is calculated by a kinematic wave model.

The key equations of Hydro-BEAM can be summarized as below. (For further details, see Kojiri [7] or Sato *et al.* [9].) For a river grid cell, water flow is calculated by a kinematic wave model for open channel. Assuming that cross-sectional shape of a river can be considered to be triangle, runoff process for a river grid cell can be described as the following equations:

$$\frac{\partial E}{\partial t} + \frac{\partial Q}{\partial x} = q_{in} \tag{1}$$

$$Q = \alpha_M A^{\frac{4}{3}} \tag{2}$$

$$\alpha_M = \frac{\sqrt{I_s}}{n}\left[I_b \Big/ \left(2\sqrt{1+I_b^{\,2}}\right)^2 \right]^{1/3} \quad (3)$$

$$I_b = \frac{B}{H} \quad (4)$$

where E = section area of water flow (m^2), Q = flow discharge (m^{3}s^{-1}), q_{in} = lateral inflow discharge per unit length (m^{3}s^{-1}), α_M = the constant of Manning's equation, I_s = the channel slope, n = Manning's friction coefficient (equivalent roughness, m$^{-1/3}$s), I_b = river bank slope,

B = the channel width (m) and H is water depth (m) at maximal high water level which is assumed to be the design flood level in this study, respectively. On the land surface and in the layer A of a grid cell which is not river channel, runoff processes are calculated by a kinematic wave model, assuming that surface flow follows Manning's equation while sub surface flow follows Darcy's law. The runoff water amounts are calculated by the following equations:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = f\gamma \quad (5)$$

$$q = \begin{bmatrix} \alpha(h-d)^{\frac{5}{3}} + ah \\ ah \end{bmatrix}, \ when \begin{bmatrix} h \ge d \\ h < d \end{bmatrix} \quad (6)$$

$$d = D\lambda, \quad \alpha = \frac{\sqrt{\sin\theta}}{n}, \quad a = \frac{k\sin\theta}{\lambda} \quad (7)$$

where h = water level (depth) (m), q = discharge per unit depth (m^{-3}s^{-1}), f = direct runoff rate which is equal to the soil saturation ratio in the layer A, γ = effective rainfall intensity (ms^{-1}), d = saturated storage level (m), D = depth of the layer A, sin θ = slope gradient (radian), a = a constant for Darcy's flow, k = saturated hydraulic conductivity and λ = effective porosity, respectively. Water flows in the layers B and C are calculated by use of a linear storage function model, and can be described as the following set of equations:

$$\frac{\partial S_B}{\partial t} = I_B - O_B, \quad O_B = (k_{BH} + k_{BV})S_B \quad (8)$$

$$I_B = (1-f)\gamma \quad (9)$$

$$\frac{\partial S_C}{\partial t} = I_C - O_C, \quad O_C = k_{CH}S_C \quad (10)$$

$$I_C = k_{BH}S_B \quad (11)$$

where S_B = storage depth (m) in the layer B, I_B = runoff input (m^{3}s^{-1}) to the layer B, O_B = runoff output from the layer B to the layer C and the river channel in the grid cell, K_{BH} = horizontal runoff coefficient (s^{-1}) of the layer B, K_{BV} = vertical runoff coefficient (s^{-1}) of the layer B, S_C = storage depth (m) in the layer C, I_C = runoff input (m3s-1) to the layer C, O_C = runoff output from the layer C to the river channel in the grid cell and K_{CH} = horizontal runoff coefficient (s^{-1}) in the layer C, respectively. Vertical infiltration from the layer C is not considered in this study assuming that the bed of the layer C is impermeable. With this model, amount of runoff water in any cell grid in the target river basin can be calculated.

OPTIMIZATION OF RESERVOIR OPERATION FOR WATER SUPPLY

Reservoir operation strategy is optimized for drought management by use of SDP model. Focusing on optimizing water supply operation of a single reservoir, the objective of the optimization problem can be considered to be minimization of drought damage caused by reservoir operation for a certain period. With this assumption, the objective of the optimization problem for SDP can be defined by the following equation:

$$\min_{R^*_{\min} \le r_t \le R^*_{\max}} \sum_{t=1}^{T_{opt}} \underset{w_t}{E}\left[H_t(w_t)\right] \tag{12}$$

where r_t = water relase at time step t, $R^*_{\min}$ = the minimal value of feasible water release, $R^*_{\max}$ = the maximal value of feasible water release, T_{opt} = the number of time steps to be optimized, w_t = river streamflow at the assessed point downstream the reservoir at time step t and $H_t(w_t)$ = drought damage function which represents the magnitude of drought impacts when streamflow is w_t at the assessed point, respectively. In this study, drought damage is assumed to increase further more if gap between water supply and demand becomes greater, and $H_t(w_t)$ is defined by the following equation [3]:

$$H_t(w_t) = \left\{\max(d_t - w_t, 0)\right\}^2 \big/ d_t \tag{13}$$

where d_t = water demand at the assessed point of streamflow downstream the reservoir at time step t. Future damage function can be described as the following equation:

$$f_t(s_t) = \min_{R^*_{\min} \le r_t \le R^*_{\max}} \underset{w_t}{E}\left\{H_t(w_t) + \underset{q_t}{E}\left[f_{t+1}(s_{t+1})\right]\right\} \quad (s_{t+1} = s_t + q_t - r_t) \tag{14}$$

where s_t = storage state at time step t and q_t = inflow to the target reservoir at time step t.

CASE STUDY

The proposed method was applied to Sameura Reservoir in the Yoshino River basin, Japan. Only water supply operation of Sameura Reservoir was focused on in this study while it is actually a multi-purpose reservoir which is also operated for flood control and power generation. The assessed point of streamflow was also assumed to locate just downstream Sameura Reservoir so as to make it easy to analyze the results although it actually locates further downstream. With this assumption, inflow to Sameura Reservoir was predicted in stead of streamflow at the assessed point by Hydro-BEAM from JMA’s Ensemble Forecasts of precipitation. The mesh size of Hydro-BEAM was set to be 1 km square, and the simulation of reservoir operation was conducted in 2007 and 2008 considering JMA’s One-month and One-week Ensemble Forecasts of precipitation.

An example of the results of ensemble inflow prediction for the coming 33 days integrating the two JMA’s ensemble forecasts of precipitation is shown in Figure 2. It can be seen in Figure 2 that the mean values of the ensemble inflow prediction tends to be more closer to the observed values compared to the historical averages, which may be considered when no prediction is considered. It can also be considered that consideration of weekly predictions (JMA-EPSW) is not always effective because their accuracy may decrease in the latter range of

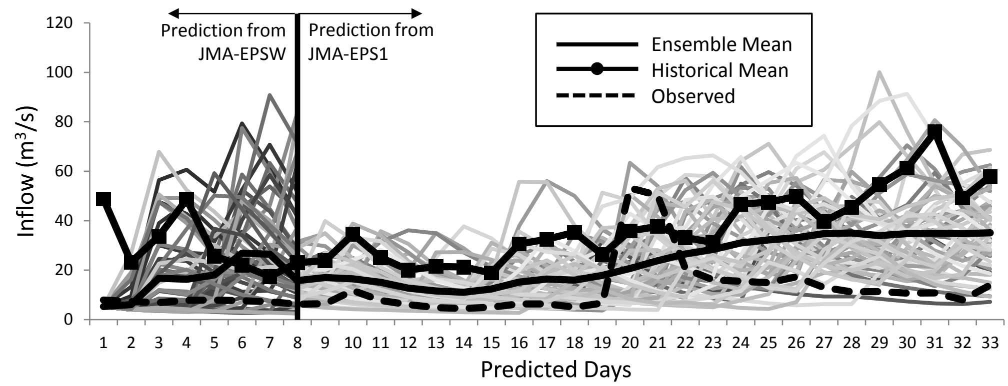

Figure 2. Example of ensemble inflow prediction results (Predicted on 31st, May, 2007)

Table 2. Averaged drought damages caused by simulated reservoir operations

Reservoir operation models	Averaged drought damage (m^3/s)		
	2007	2008	Average (2007 and 2008)
With JMA-EPS1/EPSW	0.255	1.915	1.086
With historical mean flow	0.352	2.231	1.293

forecast as seen in Figure 2 though the accuracy tended to be better in the earlier range of forecast.

Reservoir operation policy for drought management was then optimized by SDP model considering ensemble inflow prediction estimated for the coming 33 days. Averaged drought damages caused by reservoir operations according to the operation policy estimated by SDP are shown in Table 2. The averaged values for the simulated periods (2007 and 2008) are shown here. It can be seen in Table 2 that reservoir operation considering JMA-EPS1 and JMA-EPSW demonstrated better performance (smaller damage) in both 2007 and 2008 than the one considering historical mean values of inflow for the coming 33 days with assumption that no forecast was available. This is considered because the better estimation of future inflows by JMA-EPSW/EPS1 derived the better performance in optimization of reservoir operation. It can be considered that consideration of operational ensemble hydrological forecasts can be effective for real-time reservoir operation for drought management. However, more case studies are considered necessary to draw a conclusion about effectiveness of the introduction of ensemble hydrological forecasts into reservoir operation for drought management.

CONCLUSION

A real-time reservoir operation method for drought management was developed with consideration of operational One-week Forecast and One-month Forecast of precipitation provided by JMA. Ensemble inflow predictions for the coming 33 days were subsequently calculated from the ensemble forecasts of precipitation by use of Hydro-BEAM. Reservoir operation strategy was then optimized for drought management considering the ensemble inflow predictions. Through the case study applied to Sameura Reservoir in the Yoshino River basin, it was demonstrated that introduction of operational ensemble hydrological forecast to real-time reservoir operation for drought management can be effective. However, further case studies can be considered necessary to draw a conclusion about the effectiveness of the introduction of operational ensemble hydrological predictions. Ensemble prediction of inflow or streamflow can also be improved by considering a bias correction process of grid point values of operational ensemble precipitation forecast models, which were not considered in this work. Consideration of recent updates in the format of operational ensemble forecasts is also considered important as it is often updated so as to reflect advancement in techniques of forecast and observation.

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