Chapter 6
Optimization of Integrated Operation of Dams Using Ensemble Prediction

Satoru Oishi

Abstract Flood control is one of the most important issues of reservoir operation. Rivers in island countries like Japan, the Philippines, and Indonesia that have smaller reservoirs than continental countries need short-term reservoir operation for flood control. In Japan, typhoons give dominant amount of water to reservoirs. Prior releasing of water that makes effective use of the capacity of a reservoir requires the forecast of rainfall amount (hyetograph). Therefore, weather forecast of typhoons is indispensable for flood control. Oishi and Masuda (Study on optimization of the integrated dam operation using ensemble prediction in the upper reaches of the Nabari River. In: Proceedings of 35th IAHR world congress (IAHR), Chengdu, 2013) developed the reservoir control operation model using stochastic dynamic programming with one-week ensemble weather forecast. One-week ensemble forecast consists of 51 members, gives many kinds of weather variables including rainfall amount, and has a lead time of one week. In fact, the frequency of updating one-week ensemble forecast is a problem for using it. Therefore, a solution for the problem is proposed. For giving highly frequent updating, we propose to use typhoon ensemble forecast which issues four times a day, but it does not include rainfall amount. By using a similarity index with observed typhoon tracks and latest ensemble forecast result, a method to give reasonable typhoon ensemble forecasted rainfall amount has been developed. Showing the techniques and theories for managing water resources using advanced weather forecasting, we discuss about the possibility of adaptive countermeasure to manage the water resources by making the most of existing structure.

Keywords Reservoir operation • Prior releasing of water of dam • Flood control • Ensemble weather forecasting • Similarity index • Adaptive countermeasure • Stochastic dynamic programming

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6.1 Introduction

Recently, torrential rain from localized severe storm, typhoon, and so on gives serious damage to river basin. Island countries like Japan, the Philippines, and Indonesia have very steep rivers in which flood water level increases very rapidly. It expands the damage of flood in these countries.

Reservoir operation is one of solutions to protect lower river basin from severe floods which generated from rapid increasing of water level. However, ad hoc operation may be conducted under very serious condition when second water increasing might be found after all capacity for flood control has been stored by previous flood. It means optimized flood control operation model should be designed by using prediction of inflow water with high accuracy in order to reduce the damage.

A lot of researches which deal with optimized dam operation have been published. For example, Takasao et al. (1982) have applied the dynamic programming (DP) with multi-reservoir and multi-evaluation-point constraints. Sayama et al. (2010) developed a system for multi-reservoir operation with DP and distributed hydrological model in large basin.

Recently, weather forecasting system gives accurate estimation of rainfall amount for several hours. However, it is still needed to improve the accuracy when it is applied to DP because small error of prediction propagates to lead wrong operation and error of prediction is inherent.

The ensemble weather forecast has been introduced for overcoming such problem led by error propagation. Ensemble weather forecasting gives stochastic concept in order to apply weather forecasting data to reservoir operation. Ensemble weather forecasting includes spread of estimated rainfall amount which shows the probability of forecasting and uncertainty of the estimation.

The first comprehensive study which dealed with ensemble weather forecast and dam operation has been conducted by Faber and Stedinger (2001) for improving the efficiency of hydraulic power plant. Nohara et al. (2009, 2011) estimated inflow discharge by taking each ensemble member into consideration. Eum and Kim (2010) studied the updating procedure of ensemble weather forecast for long-term reservoir operation.

In this chapter, the reservoir control operation model using stochastic dynamic programming with one-week ensemble weather forecast is explained by using a result of Oishi and Masuda (2013). One-week ensemble forecast consists of 51 members and gives many kinds of weather variables including rainfall amount. In fact, the frequency of updating one-week ensemble forecast is a problem for using it. Therefore, a solution for the problem is proposed. For giving highly frequent updating, we propose to use typhoon ensemble forecast which issues four times a day, but it does not include rainfall amount. By using a similarity index with observed typhoon tracks and latest ensemble forecast result, a method to give reasonable typhoon ensemble forecasted rainfall amount has been developed, and it will be explained in this chapter.

6.2 Capacity of Reservoir and Prior Releasing of Water

The total capacity of reservoir consists of flood control capacity, consumptive use capacity, inactive capacity, and dead capacity. Most of the time, there is an empty space without water in a reservoir. Volume of the empty space is defined as flood control capacity in most of reservoirs. The space will be filled by water during flood for decreasing water level at the lower part of river basin during flood. We call the activity to fill the reservoir by flood as "cutting a peak of discharge."

Flood control capacity and consumptive use capacity are clearly distinguished in order to avoid conflict. Therefore, a lot of multipurpose dams always look empty during rainy season because flood control capacity is without water all through the rainy season which is basically from May to October in Japan. However, in more than 99 % of days, the empty storage is useless. Moreover, recent numerical weather prediction gives better prediction of rainfall than decades before. Therefore, storing water in flood control capacity and releasing the same amount of water as flood control capacity before the rainfall comes can give benefit to water resources management. However, this kind of prior releasing of water in flood control capacity is not the target of the present chapter because it has more risk than the other type which is described in the following.

In the present chapter, the target is to release stored water in consumptive use capacity before the rain comes. There is not a risk of artificial flood but risk of artificial drought during releasing water in consumptive use capacity. Artificial drought happens when the amount of water released in prior to flood is more than the amount of water that rain gives. The risk of drought can be compensated by water given by rain forecasted. For example, we can release one million cubic meters when predicted total amount of discharge is more than one million cubic meters. Moreover the prior releasing of water gives safely controlled flood before the rain and cutting a peak of discharge.

The procedure of prior releasing of water with perfect prediction of rainfall having enough lead time consists of the following:

1. predicting rainfall,
2. calculating discharge,
3. calculating optimized amount of releasing water,
4. making a plan to release water under consideration of dam operational rule.

However, weather forecast is actually not perfect. There is uncertainty and reviews of the predictions are always necessary. The following section deals with the topics.

6.3 Numerical Weather Prediction System in Japan and Its Uncertainty

Numerical weather forecasting model has widely been used for predicting rainfall amount. However, incompleteness of observational data, not perfect understanding of atmospheric process, and chaotic behavior of nonlinearized numerical system lead to expansion of small error in a prediction. Therefore, recently ensemble numerical weather prediction system is developed as well as deterministic numerical weather prediction system.

Ensemble numerical weather prediction system starts from many initial conditions to analyze the spread of forecast. The spread is uncertainty in another word. Narrow spread gives relatively more certain forecast than wider spread. Usually, we assume the median of histogram of estimated rainfall amount calculated by ensemble weather prediction system. However, using each individual ensemble member for calculating the optimized reservoir control produces risk information generated by the optimization including probability of water level in lower river basin and confidential level of the operation.

The following sentences explain weather prediction system including deterministic one and ensemble one.

The operational weather prediction system in Japan Meteorological Agency (JMA) has two types, deterministic weather prediction model and ensemble weather prediction model. Deterministic weather prediction model consists of global spectral model (GSM), mesoscale model (MSM), and local forecast model (LFM). GSM uses hydrostatic assumption, whereas MSM and LFM are non-hydrostatic model. The difference between MSM and LFM is the resolution; MSM has 5 km interval grid, and LFM 2 km. Ensemble weather prediction model is based on GSM, and it consists of four types, weekly ensemble prediction system (WEPS), typhoon ensemble prediction system (TEPS), monthly ensemble prediction system, and seasonal ensemble prediction system.

JMA releases result of WEPS once a day from March 2001 by using a kind of general circulation model (GCM). JMA starts calculating WEPS from 21 Japan Standard Time (JST) which is Greenwich Mean Time (GMT) plus 9 h, and it issues WEPS at four JST after numerical calculation. WEPS contains 51 ensemble sets of prediction which has six hourly data, nine days of lead time, both longitudinal and latitudinal resolution of 1.25°, and four vertical layers (surface, 925, 850, 700, and 500 hPa). WEPS comprises physical variables as surface pressure, altitude, temperature, wind speed, wind direction, humidity, and surface rainfall amount.

JMA has also released results of TEPS since February 2008. JMA issues results of TEPS when typhoons exist or a tropical cyclone forecasted to be a typhoon exists. For making TEPS, JMA uses the same numerical model as WEPS. JMA calculates TEPS four times a day (03, 09, 15, 21 JST). TEPS contains 11 ensemble sets of prediction which has the position (longitude and latitude) and pressure of typhoon

Table 6.1 Numerical ensemble weather prediction system in JMA

Model	Region, resolution	Number of layers	Forecasting time initial time (UTC)	Number of members
Weekly ensemble prediction system (WEPS)	Horizontal resolution Entire earth About 40 km	60 layers	264 h 00, 12	27
Previous WEPS used until February 2014	Entire earth About 150 km		264 h 12	51
Typhoon ensemble prediction system (TEPS)	Entire earth About 40 km	60 layers	132 h 00, 06, 12, 18	25
Previous TEPS used until March 2014	Entire earth About 150 km		132 h 00, 06, 12, 18	11
Monthly ensemble prediction system	Entire earth About 55 km Abnormal weather detection	60 layers	18 days Saturday Sunday	25
Monthly ensemble prediction system	Entire earth About 55 km Monthly weather tendency	60 layers	35 days Tuesday Wednesday	25
Seasonal ensemble prediction system	Entire earth Atmosphere 180 km Ocean 100 km	Atmosphere 40 Ocean 50	7 months 5 days of interval	51

center and wind speed. By using TEPS, we can expect the following advantage: (i) high frequency of TEPS reduces error of prediction; (ii) prediction of typhoon track and its spread gives better reliability.

The detail specifications of JMA weather prediction systems are shown in Table 6.1.

6.4 Dam Discharge Optimization Model

6.4.1 Background

In this section, weekly ensemble weather forecast issued by Japan Meteorological Agency has been introduced into integrated operation of multi-reservoir system in order to develop a short-term flood control model which reduces the water level of the river. Stochastic dynamic programming is used for decision-making of releasing water from three reservoirs with the ensemble forecast. A flood that happened in

Nabari River basin where river authorities conducted their integrated operation of multi-reservoirs without the ensemble forecast was selected as a case study. Water level calculated by the proposed method has been compared with the result of actual decision made by the authority, one calculated under ideal condition of hundred-percent weather forecast and one brought by following an existing rule. Then the proposed method obtained the best solution.

6.4.2 *Dynamic Programming for Deciding Dam Discharge*

Dynamic programming (DP) developed by R. Bellman (1957) is a method of operational research. DP gives the optimized solution by dividing the problem into smaller subproblem. DP is based on the principle of optimality.

In the present chapter, the target of optimization is minimizing the discharge at evaluating point which is a certain point in the lower river basin. Then, the objective function up until time T is defined as follows:

$$\min_{O(n,t)} \sum_{t=1}^{T} \{D\,[Q(t)]\} \tag{6.1}$$

where $O(n, t)$ is the discharge from dam n at time $t(t = 1, \ldots, \mathrm{T})$, $Q(t)$ is the discharge at the evaluating point, and $D(Q(t))$ is the evaluation function at time t. The evaluation function in which we assume the damage of flood is proportional to the square of discharge when embankment is washed out is defined as follows:

$$D\,[Q(t)] = \left\{ \frac{Q(t)}{Q_{id}} \right\}^2 \tag{6.2}$$

where Q_{id} is the design flood at the evaluating point. Please notice that the $D\,[Q(t)] > 1$ means exceeding the design flood (Takasao et al. 1982).

Constraints of dams which are decided by physical aspects of dams and their operational rule are formulated as follows:

$$\begin{aligned} S_{\min}(n) \le S(n, t) \le S_{\max}(n) \\ O_{\min}(n) \le O(n, t) \le O_{\max}(n) \end{aligned} \tag{6.3}$$

where $S(n, t)$ is the amount of stored water in dam n at time t, $S_{\min}(n)$ is the minimum amount of storage of dam n, $S_{\max}(n)$ is the maximum capacity of dam n, $O_{\min}(n)$ is the minimum discharge from dam n, and $O_{\max}(n)$ is the maximum discharge from dam n.

The continuous equation for stored water at each dam is formulated as follows:

$$S(n, t + 1) = S(n, t) + I(n, t) - O(n, t) \tag{6.4}$$

where $I(n,t)$ is the inflow to dam n at time t. The discharge at the evaluating point is calculated as summation of discharge from each dam, upstream, and remaining basin as follows:

$$Q(t) = \sum_i O(i,t). \tag{6.5}$$

Then, we define the problem as the minimization of cost function $f_t(s(1,t), s(2,t), s(3,t))$ from arbitral time t to the end T by optimizing the discharge from each dam.

By using the principle of optimality, the objective function has the following relationship:

$$\begin{aligned} &f_t(S(1,t), S(2,t), S(3,t)) \\ &= \min_{O_{\min}(n) \leq O^*(n,t) \leq O_{\max}(n)} \left\{ D\left[Q(t)\right] + f_{t+1}(S(1,t+1), S(2,t+1), S(3,t+1)) \right\}. \end{aligned} \tag{6.6}$$

Moreover, the future cost function $f_T(S(1,T), S(2,T), S(3,T))$ is uniquely defined as the following:

$$f_T(S(1,T), S(2,T), S(3,T)) = D\left[Q(T)\right]. \tag{6.7}$$

Therefore, we calculate the following equation step-by-step, $f_{T-1}, \cdots f_1$, and the initial condition of stored water in the dams was given as

$$\{S(1,1), S(2,1), S(3,1)\} = \{S^*(1,1), S^*(2,1), S^*(3,1)\};$$

then, the optimized solution is given as $f_1(S^*(1,1), S^*(2,1), S^*(3,1))$, and the optimized discharge from each dam is calculated as follows: $\{O^*(1,t), O^*(2,t), O^*(3,t)\}$

$$\begin{aligned} &\{O^*(1,t), O^*(2,t), O^*(3,t)\} \\ &= \min_{O_{\min}(n) \leq O^*(n,t) \leq O_{\max}(n)} \left\{ D\left[Q(T)\right] + f_{t+1}(S(1,t+1), S(2,t+1), S(3,t+1)) \right\} \cdot \end{aligned} \tag{6.8}$$

6.4.3 Stochastic Dynamic Programming for Deciding Dam Discharge

Stochastic dynamic programming (SDP) expresses the objective function as the expected value by considering discharge at each time with probabilistic distribution. Then, it is used for optimization using ensemble weather forecast.

The cost function is defined as follows by using stochastic process $P[I(t)]$ which is independent in terms of time series:

$$\begin{aligned}&f_t(S(1,t),S(2,t),S(3,t))\\&=\min_{O_{\min}(n)\leq O^*(n,t)\leq O_{\max}(n)}\left\{\sum_{I(t)}D\left[Q(t)\right]+f_{t+1}(S(1,t+1),S(2,t+1),S(3,t+1))P\left[I(t)\right]\right\}\end{aligned}\quad(6.9)$$

Generally, equivalent probability for each ensemble member can be assumed. Therefore, $P[I(t)]$ in Eq. 6.9 is defined as follows:

$$P[I(t)^m]=1/M.\quad(6.10)$$

The objective function and cost function are defined as follows:

$$\min_{o(n,t)}\sum_{t=1}^{T}\left\{\frac{1}{M}D\left[Q(t)^m\right]\right\}\quad(6.11)$$

$$\begin{aligned}&f_t(S(1,t),S(2,t),S(3,t))\\&=\min_{O_{\min}(n)\leq O^*(n,t)\leq O_{\max}(n)}\left\{\tfrac{1}{M}D\left[Q(t)^m\right]+f_{t+1}(S(1,t+1)^m,S(2,t+1)^m,S(3,t+1)^m)\right\}\end{aligned}\quad(6.12)$$

Then the optimized discharge from each dam, $\{O^*(1,I(1,t)^m,t),O^*(2,\ I(2,t)^m,t),$ $O^*(3,I(3,t)^m,t)\}$, is calculated by using the following equation:

$$\begin{aligned}&\{O^*(1,I(1,t)^m,t),O^*(2,I(2,t)^m,t),O^*(3,I(3,t)^m,t)\}\\&=\min\{\tfrac{1}{M}D\left[Q(t)^m\right]+f_{t+1}(S(1,t+1)^m,S(2,t+1)^m,S(3,t+1)^m)\}\end{aligned}\quad(6.13)$$

6.4.4 *Application Result*

6.4.4.1 Target Dams

In the present chapter, the dam operation model described above has been applied to Nabari River basin where the cities in the lower basin were threatened by flood under typhoon no. 18 in 2009 (T0918, MELOR). Nabari River flows through Nabari City in Mie Prefecture and it is one of tributaries of Yodo river system. There is a confluence of Shorenji River and Uda River in the upper part, and Nabari River joins to Kizu River in the lowest end. Hinachi Dam locates in the upper part of Nabari River, Shorenji Dam in the upper part of Shorenji River, and Muro Dam in the upper part of Uda River. These dams are multipurpose dams which include purpose of flood control, irrigation, hydraulic power plant, and domestic water supply.

Typhoon T0918 made landfall in Chita Peninsula at 5AM JST of October 8, 2009, then it passed through Honshu Island to reach the southeast coast of Hokkaido Island. The typhoon killed 5 and injured 132 all over Japan, and it collapsed 4328 houses. The typhoon approached Nabari City in the dawn of October 8, 2009. The city was threatened by flood brought by the typhoon. Therefore, Kizukawa Dam integrated management office of Japan Water Agency (JWA) with Yodogawa

Dam integrated management office of Japanese Ministry of Land Infrastructure, Transport and Tourism (MLIT) took ad hoc operating procedure which has been examined in advance. In the procedure, they took the water level, rainfall amount, and storage capacities of three dams into account for integrating flood control action to store the water by reducing the discharge from dams. Then, the ad hoc procedure decreased the water level of Nabari point which is evaluating point for flood control by 1.5 m from calculated water level without taking action. The action contributed to avoid flood damage for 1,200 houses.

6.4.4.2 Dam Operational Rule and Dam Operation

The three dams in the upper part of the basin has their flood control rules which regulate flood control starting discharge. Before the inflow into each dam reached the flood control starting discharge, releasing discharge from each dam was equal to the inflow. Then, it reached the flood control starting discharge, releasing discharge was fixed to the flood control starting discharge, and the remaining amount of inflowing water should be stored by dams.

However, the dam integrated management offices took ad hoc operating procedure. The inflow into each dam reached the flood control starting discharge at the afternoon of October 7 and flood control has been started. The weather forecast at the moment predicted less rainfall amount than the one that actually happened. However, the typhoon route was changed at 2AM October 8; then rainfall amount increased to lead prediction of water level at Nabari point which exceeded the warning level. Therefore, dam integrated management offices took action for storing water in the reservoirs by reducing the releasing discharge from 3:15AM. This flood control action soon gave risk of shortage of capacity of Shorenji Dam which has the smallest capacity in the three dams at 3:40. Then, they investigated the situation of water level and remaining reservoir capacity carefully, then they increased releasing discharge from Shorenji Dam as well as decreased releasing discharge from Hinachi Dam which has the largest capacity in three dams. At 4:40, weather forecast estimated less amount of rain at Muro Dam basin than previous estimation, then they reduced the releasing water discharge from Muro Dam leading reduction of water level at Nabari point. Finally, they reconsidered the operation action 10 times within 2 h resulting to avoid flood in Nabari City. The inflow into and outflow from each dam have been recorded in hydrology and water quality database of MLIT (Database for Hydrology and Water Quality in Japan 2012) which has been used for the present chapter as data of comparison.

6.4.4.3 Modeling of Target Basin

The model of the target basin including Hinachi Dam, Shorenji Dam, and Muro Dam is shown in Fig. 6.1. The amount of releasing water discharge from each dam was optimized in the present chapter by calculating inflow of each subsection using forecasted rainfall amount.

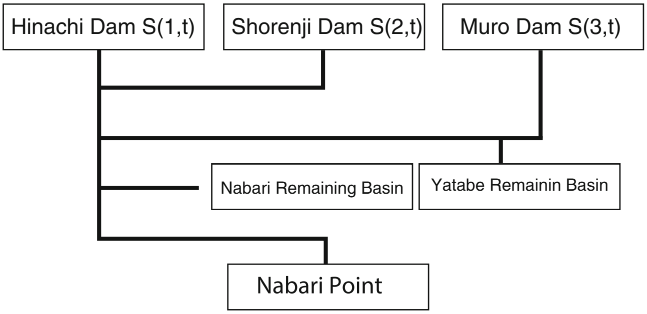

Fig. 6.1 Model of target basin

Table 6.2 Runoff coefficients and basin area

	Runoff coefficient	Basin area [km^2]
Hinachi Dam	0.39	75.8
Shorenji Dam	0.65	100.7
Muro Dam	0.40	134.9
Hinachi River	0.50	75.5
Shorenji River	0.50	100.0
Uda River	0.50	136.0
Yatabe remaining basin	0.50	70.8
Nabari remaining basin	0.50	51.4

6.4.5 Flood Prediction by Using Ensemble Weather Prediction

One-week ensemble weather forecast issued from JMA daily at 21:00 JST has been used in the present chapter as grid point value (GPV). The grid point of 33.75N and 136.25E was selected as the nearest point to Nabari City. The one-week ensemble weather forecast has 6 h interval for rainfall amount estimation; then, linear interpolation was applied to obtain the hourly rainfall amount.

AMeDAS rainfall amount at Nabari AMeDAS point (34.64N, 136.11E) was selected as data of perfect forecast.

Rational equation which is for calculating peak discharge in small river basin has been used for converting estimated rainfall amount into time series variation of discharge:

$$Q = \frac{1}{3.6} f r_i A_i \tag{6.14}$$

where Q[m^3/s] is the discharge, f is the runoff coefficient, r_i[mm/h] is the rainfall intensity, and A_i[km^2] is the basin area. Runoff coefficients and area were referred from Table 6.2 published by Kinki Regional Office of MLIT in November 2009.

H-Q equation for converting water level at Nabari point to the discharge is

$$\begin{cases} Q = 46.51(H-2.2)^2 \ H \leq 5.24 \\ Q = 72.77(H-2.8)^2 \ H \leq 5.25 \end{cases} \tag{6.15}$$

6.4.5.1 Objective Function and Constraints

The comparison among optimized dam operation with one-week ensemble weather forecasting issued from JMA, one with mean of ensemble weather forecasting and one with perfect forecasting using rain gauge observation data, operation under flood control rules regulated in dam operation manual, and ad hoc operation activity taken by the dam integrated management offices, has been conducted in the present chapter in order to evaluate the model. DP has been applied for mean of ensemble weather forecasting, perfect weather forecasting, and SDP for ensemble weather forecasting.

From H-Q equation at Nabari point, $Q_{id} = 1,893\,\mathrm{m}^3/\mathrm{s}$ was calculated from design flood water level of 7.99 m.

The constraints were decided as follows:

1. In case stored water amount is less than maximum normal level:
   Hinachi Dam $0 \leq S(1,t) \leq 1,430 \times 10^4\,\mathrm{m}^3$
   Shorenji Dam $0 \leq S(2,t) \leq 2,380 \times 10^4\,\mathrm{m}^3$
   Muro Dam $0 \leq S(3,t) \leq 1,840 \times 10^4\,\mathrm{m}^3$.
2. In case inflow into each dam exceeds flood control starting discharge, the amount exceeding flood control starting discharge should be stored in the reservoir. In the present chapter, prior releasing is allowed for optimized dam operation within the amount less than flood control starting discharge:
   Hinachi Dam $0 \leq O(1,t) \leq 300\,\mathrm{m}^3/\mathrm{s}$
   Shorenji Dam $0 \leq O(2,t) \leq 450\,\mathrm{m}^3/\mathrm{s}$
   Muro Dam $0 \leq O(3,t) \leq 300\,\mathrm{m}^3/\mathrm{s}$.

6.4.5.2 Optimization Results and Discussions for Applied Models

In the following sections, we defined terminology as follows for explaining the comparison among them:

SDP operation: stochastic dynamic programming optimization with ensemble weather forecast,

Ensemble mean DP operation: dynamic programming optimization with mean of ensemble weather forecast,

Perfect DP operation: DP optimization with actually collected rainfall data as a perfect weather forecasting,

Ad hoc operation: ad hoc operation activity taken by the dam integrated management offices conducted,

Regular operation: operation under flood control rules regulated in dam operation manual.

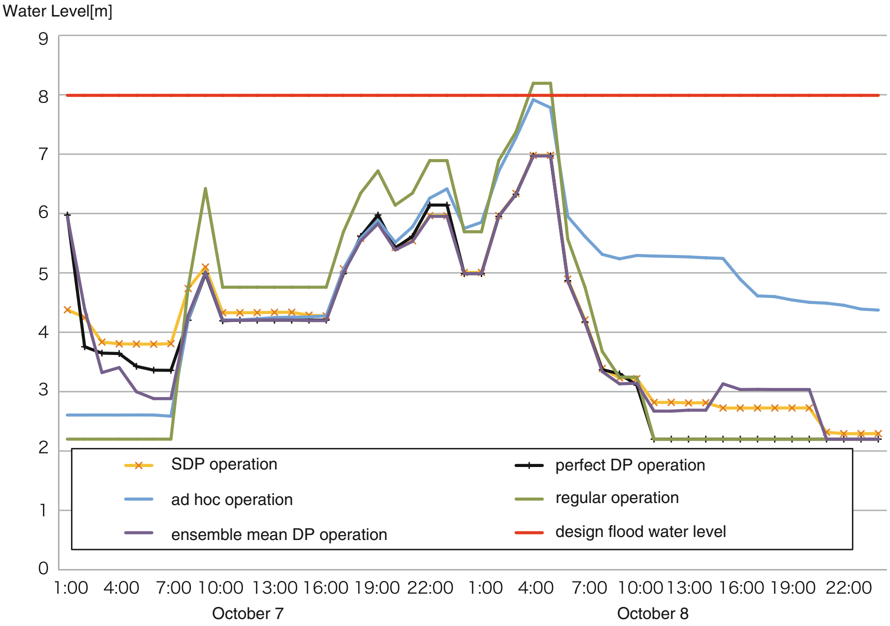

Fig. 6.2 Time series variation of water level at Nabari evaluating point by optimized flood control using SDP

The water level at Nabari flood evaluating point and stored water amount in each of Hinachi, Shorenji, and Muro Dam are shown in Fig. 6.2.

Figure 6.2 indicates that regular operation gives maximum water level (MWL) of Nabari point that was estimated as 8.2 m at 4:00 to 5:00AM JST of October 8. It means that regular operation could not prevent water level from exceeding design flood level. Ad hoc operation reduced MWL to 7.9 m which is less than design flood level; perfect DP operation and SDP operation give MWL of 7.0 m which is much less than ad hoc operation. It suggests that SDP using ensemble weather forecast gives better information for flood control action.

Deeper analysis inside each operation reveals that the SDP operation and perfect DP operation decide prior flood control operation by using Shorenji Dam and Muro Dam which was not conducted by ad hoc operation. Moreover, perfect DP operation stops releasing water from all dams after 17:00 of October 7, whereas SDP operation decides to reduce the releasing water from all dams to the lowest amount. The perfect DP operation decided to store water up to maximum flood control capacity, and SDP operation gave reserve storage as $3.2 \times 10^5\,\text{m}^3$ in Shorenji Dam and $5.1 \times 10^5\,\text{m}^3$ in Muro Dam. Hinachi Dam has so large capacity to store the flood discharge that SDP operation and perfect DP operation decided to store all of the inflow discharge into Hinachi Dam.

In ensemble mean DP operation did not give appropriate optimization because of the difference between mean rainfall amount of weather forecast and observed rainfall amount resulting that stored water in Shorenji Dam and Muro Dam exceeded their maximum storage capacity.

6.4.5.3 Discussion by Varying the Objective Function

The cause of ensemble mean DP operation exceeded the maximum storage capacities that were deeply investigated by assuming it as the formulation of cost function with square of discharge at Nabari point. Then, the formulation of cost function was changed into linear of the discharge and third power of it. Figure 6.3 shows the water level at Nabari point. In Fig. 6.3 ensemble mean DP operation was applied with cost function of square of discharge (shown as square of discharge), linear of discharge, and third powered discharge. Figure 6.3 contains the result of perfect DP operation and SDP operation both of which have cost function of square of discharge for comparison.

Figure 6.3 shows that higher water level at Nabari point was estimated by using cost function of linear and square of discharge leading to the decision of more amount of releasing water as prior flood control. Cost function using third powered discharge estimated lower water level at Nabari point leading to less amount of prior flood control releasing. The following decisions after 10:00AM JST of October 7 were almost the same. Therefore, the formulation of cost function affected prior flood control decision.

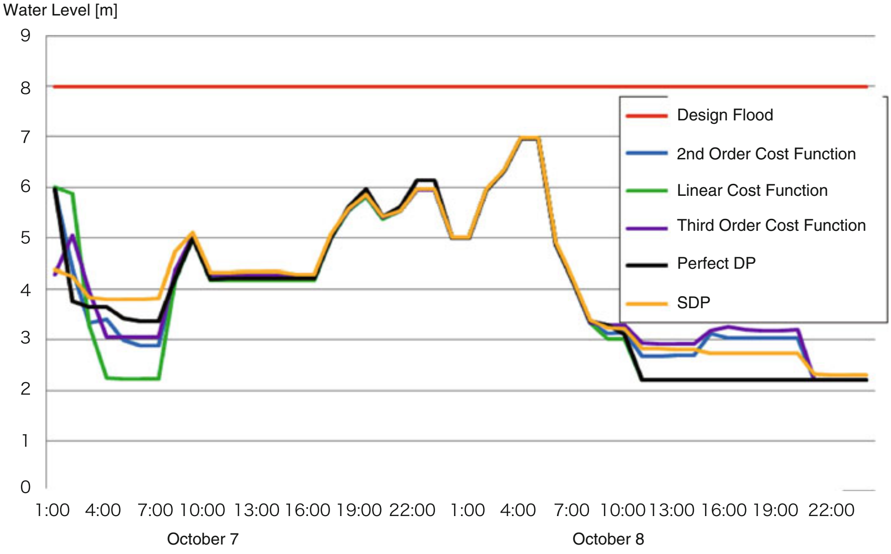

Fig. 6.3 Variation of water level by changing the order of the cost function

The difference of stored water amount at each dam was investigated in order to understand the effect of prior flood control decision to stored water amount. They decided that all inflow discharge into Hinachi Dam was stored and there was no difference. On the other hand, less prior flood releasing when they use cost function of third powered discharge resulted in the exceeding stored water amount of $3.2 \times 10^5\,\mathrm{m}^3$ for Shorenji Dam and $3.3 \times 10^5\,\mathrm{m}^3$ for Muro Dam from the maximum flood control capacity of each dam. The linear cost function increases the amount of prior flood releasing from dams resulting in that they remained reserve capacity from flood control capacity more than $3.5 \times 10^5\,\mathrm{m}^3$ for Shorenji Dam and $3.0 \times 10^5\,\mathrm{m}^3$ for Muro Dam.

In summary, higher-order cost function gave decision of less releasing water and reducing water level at Nabari point, whereas lower-order cost function gave more releasing water and reducing water level of each dam. Finally, the second order of discharge was appropriate to the cost function in the present case also.

6.4.5.4 Optimization of Dam Discharge by Taking Prediction with More Dangerous Rain

Instead of using mean of ensemble, larger and rapidly increasing rainfall forecasted in ensemble weather forecast was selected to optimize the flood control in order to consider the safer operation of dams. Safer operation was brought from dangerously forecasted rainfall which means an ensemble member with the largest amount of rainfall within ensemble members, a member with the shortest term from the starting rainfall to the peak of it, and members with multiple peaks. In the present chapter, the following ensemble members were used: (i) the member with total rainfall amount of 263 mm ($E = 50$), (ii) the member which predicted peak of rain earlier than the actual peak and strongest rainfall intensity of 17.3 mm/h ($E = 43$), and (iii) the member which has prediction closer to both (i) and (ii) with prediction of the total amount of rainfall as 251 mm and of maximum rainfall intensity as 16.7 mm/h. The actual total amount of rainfall was 188 mm.

Figure 6.4 shows water level optimized by using each ensemble member with dangerous prediction.

Figure 6.4 indicates that dangerous prediction increased prior flood releasing from dams in order to avoid exceeding amount of flood control capacity. Therefore, larger amount of reserve capacity remained as $4.0 \times 10^6\,\mathrm{m}^3$ in Shorenji Dam and $3.0 \times 10^6\,\mathrm{m}^3$ in Muro Dam. When $E = 50$ which predicted the largest amount of rainfall in the last half of rainfall period was used for optimization, it decided to release water from dams in the first half of rainfall period; then it decided to store water in dams. However, the stored water has exceeded total capacity for flood control at 15:00 JST of October 8; then it released water after the peak leading to rising water level at Nabari point by too much release from dams.

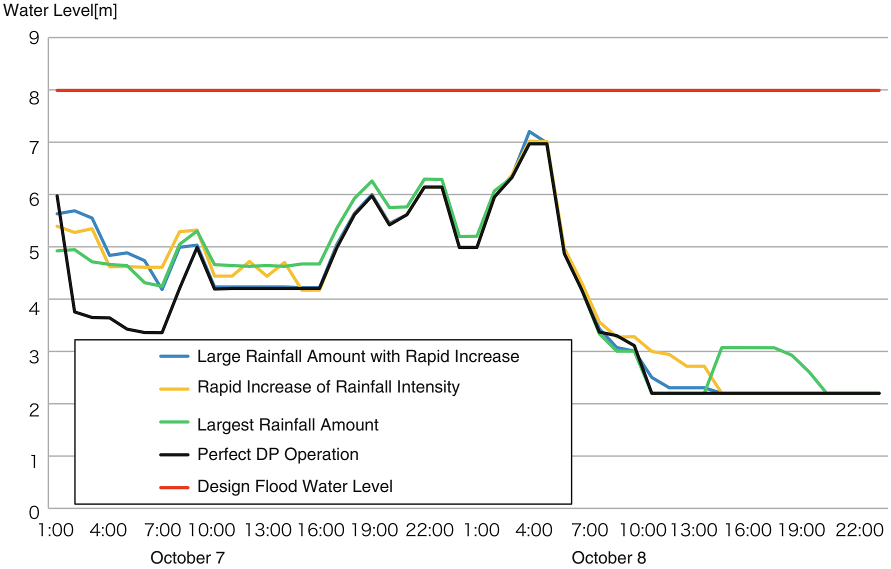

Fig. 6.4 Optimized water level by using ensemble members with dangerous prediction

6.5 Efficiency of Frequent Update of Ensemble Prediction

6.5.1 Background

Oishi and Masuda (2013) developed the reservoir control operation model using stochastic dynamic programming (SDP) with one-week ensemble weather forecast (WEP) made by weekly ensemble prediction system (WEPS) issued by Japan Meteorological Agency (JMA). WEP consists of 51 members and gives many kinds of weather variables including rainfall amount.

In fact, the frequency of issuing WEP is daily which is less frequent than the requirement and it raises a problem for using WEP. In the present chapter, a solution for the problem by using typhoon ensemble prediction (TEP) made by typhoon ensemble prediction system (TEPS) issued by JMA is proposed.

6.5.2 Uncertainty Analysis of TEPS and WEPS

TEPS has uncertainty because of their limitation of measurement, initial condition setting, and numerical specifications. Here, the problem that comes from numerical simulation is described.

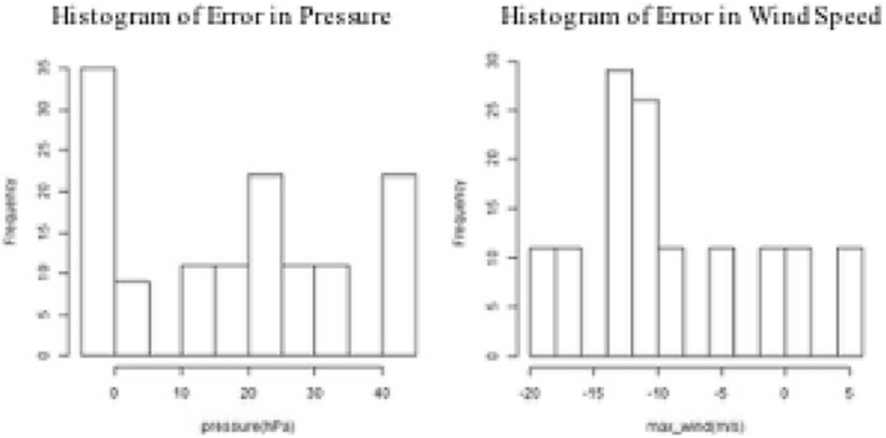

Fig. 6.5 Tendency of the prediction error in pressure (*left*) and wind speed (*right*)

The disadvantage of TEPS is their limitation of predicting pressure of typhoon center. For predicting the pressure of typhoon center accurately, it requires 5 km resolution of numerical simulation, whereas the GCM has 60 km resolution. The limitation of numerical resolution gives higher pressure as a prediction than actual situation. Then, the wind speed also is predicted weaker than actual. Figure 6.5 shows the tendency of the prediction error which is defined with observation level from the predicted value. The figure shows that pressure tends to be higher and the wind speed weaker in prediction.

As the purpose of ensemble numerical prediction, a WEPS has a range of predicted value which is called a “spread.” Figures 6.6 and 6.7 show a better example and a worse example of the spread of rainfall amount, respectively. Figure 6.6 shows the result of WEPS for typhoon no.17 in 2012 (T1217), JELAWAT, and Fig. 6.7 for typhoon no. 09 in 2011, MUIFA. Both Figs. 6.6 and 6.7 have horizontal axis showing time and three vertical axes showing the total amount of rainfall updating daily. A horizontal line shows the observed rainfall amount which is the correct value. Horizontal bars show the histogram of predicted amount of rainfall by WEPS. A set of horizontal bars starting from one vertical axis means a set of prediction spread obtained from a set of ensemble forecast issued daily. The bar graph in black color stretching downward from the horizontal arrow line in the lower part expresses hyetograph. Figure 6.6 shows the reducing of uncertainty of prediction where the spread of the left side of the figure is wide and one of the right side is sharp. Figure 6.7 shows the worst ensemble prediction among the present chapter which firstly gave lower amount of rainfall as forecast, and then prediction increased the amount of rainfall time by time and finally gave the overestimation.

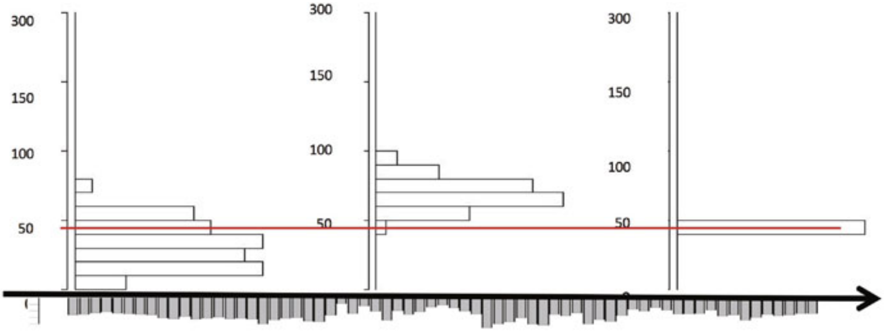

Fig. 6.6 Transition of spread of WEPS for T1217; *red line* shows the total amount of rainfall; three vertical axes show updating of WEPS and predicted rainfall amount; horizontal bars show histogram; vertical bar in *gray color* shows hyetograph

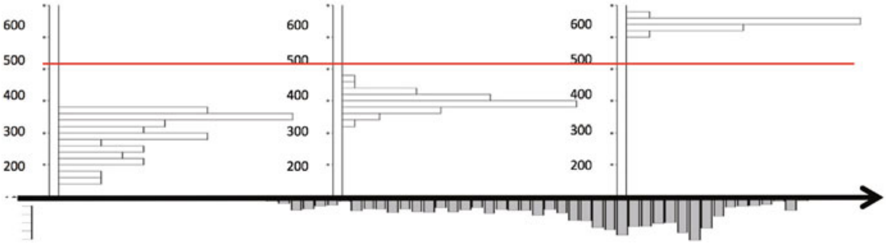

Fig. 6.7 Transition of spread of WEPS for T1109; *red line* shows the total amount of rainfall; three vertical axes show updating of WEPS and predicted rainfall amount; horizontal bars show histogram; vertical bar in *gray color* shows hyetograph

6.5.3 Combining of TEPS and WEPS

6.5.3.1 Development of the Combined Model

In order to obtain more frequent ensemble rainfall forecast by using TEPS (four times a day), a model that combines TEPS and WEPS (once a day) has been developed. The concept of the combined model uses similarity of physical variables between TEPS and WEPS. Moreover rainfall amount of similar WEPS ensemble member is assigned to corresponding member of TEPS.

In order to measure the similarity, first, the impact of each variable on forecasting rainfall amount has been analyzed by multiple regression analysis in which correlation among errors of each predicted variable in WEPS such as rainfall amount at a target point as an explained variable, longitude and latitude of typhoon center, distance between typhoon center and target point, and center pressure of the typhoon and wind speed as explaining variables. Table 6.3 shows results of multiple regressions. It shows that correlation coefficient R2 was less than 0.5 in 2012 and 2013. It means some revision of WEPS has been accomplished and numerical

Table 6.3 Result of multiple regressions among rainfall amount with the other physical variables

		t-value				
Date	R2	Distance	Latitude	Longitude	Pressure	Wind speed
918	0.2	0.71	−0.96	−1.31	6.00	2.61
1004	0.73	3.61	−1.4	3.35	−13.37	−0.17
1007	0.64	1.59	−7.46	6.65	9.63	6.06
1009	0.79	−5.88	−6.61	5.95	−14.65	−1.18
1109	0.68	−2.89	−4.98	0.75	5.74	−0.54
1115	0.74	−2.37	2.49	−4.62	1.06	−8.66
1204	0.03	1.03	−2.22	1.25	−0.85	−0.2
1210	0.24	3.91	0.25	−1.91	−4.3	−0.74
1215	0.47	1.22	−3.08	2.04	−10.28	0.88
1216	0.1	−3.83	3.36	−1.52	−2.74	−0.08
1217	0.2	1.52	1.77	−0.01	3.37	2.29
1304	0.38	1.23	5.67	−0.69	−6.19	−0.02

ensemble prediction has been improved to have less correlation in errors of physical variables including rainfall amount. Even correlation coefficient were low, t-value of the error of pressure toward the error of rainfall amount has significant value. Therefore, we are using pressure as an index of similarity. However, the track of the center of typhoons was thought to be an index of similarity; therefore, we are using distance as the other index of similarity. Finally, we proposed a couple of combined model of TEPS and WEPS by using similarity of distance which is called TEPS_WEPS(distance) model and using similarity of distance and pressure which is called TEPS_WEPS(distance, ps) model.

Figure 6.8 shows an example on T1217 where the forecast of WEPS was reasonable as shown in Fig. 6.6. It shows the time series variation of observed rainfall shown as amedas, mean of WEPS forecasts, TEPS_WEPS(distance) model forecasts, and TEPS_WEPS(distance, ps) model forecasts. According to Fig. 6.8, these models gave reasonable forecasts. Figure 6.9 shows the other example on T1109 where the forecast of WEPS was not good as shown in Fig. 6.7. When the WEPS was worse, the proposed model of TEPS_WEPS gave slightly better forecast.

Table 6.4 shows summary of the root mean square error (RMSE) of the forecast for all typhoon which the present chapter has dealt with. According to Table 6.4, TEPS_WEPS (distance, ps) model gave smaller RMSE than WEPS in 7 out of 14 typhoons. Deeper analysis for T1106 and T1112 has been conducted because TEPS_WEPS (distance, ps) gave much bigger RMSE in these typhoons. It was rain in the southern part of Shikoku Island where topography usually affects the rainfall distribution during passing of a typhoon. The model proposed in the present chapter did not take such a local topography into account. Then, the model gave worse forecast than WEPS model which took the topography into account. However, our target basin in the study was not in southern part of Shikoku Island. Then, we can use the result of model with reasonable accuracy.

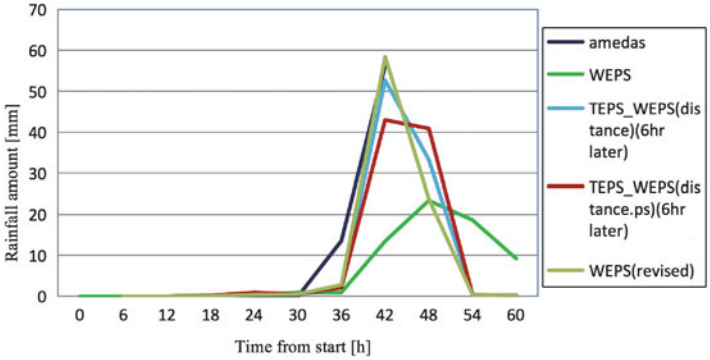

Fig. 6.8 Result of observed (amedas) and forecasted (the other) amount of rainfall in the case of T1217

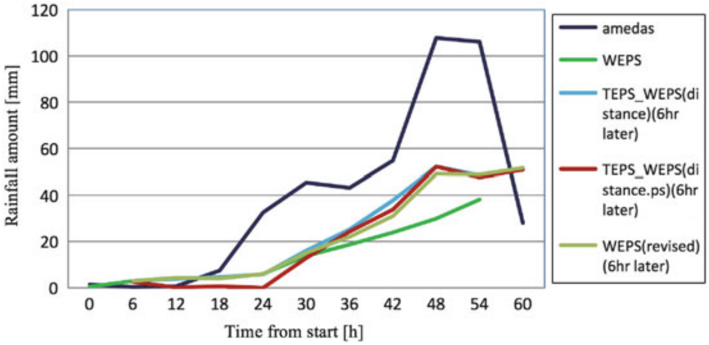

Fig. 6.9 Result of observed (amedas) and forecasted (the other) amount of rainfall in the case of T1109

6.5.4 Application of TEPS_WEPS Model to Reservoir Operation

The result is shown in Table 6.5 as damage function which gives smaller amount as better operation. Table 6.5 shows that the best operation has been done by using DP with perfect forecast and the second best was SDP by using all ensemble members of WEPS. TEPS_WEPS(distance) gave slightly worse result than DP by using ensemble mean.

Figure 6.10 shows the water level at a point at which the river authority evaluates the river water level for flood control. Figure 6.10 consists of various results in which red horizontal line was the design flood water level, gray is the result of operation under flood control rules regulated in dam operation manual, and light blue is one of ad hoc operations taken by the dam integrated management offices and ones

Table 6.4 Root mean square error of rainfall forecast made by WEPS and models proposed

RMSE	Available from 6 h later				Available from 12 h later		
(mm)	WEPS	TEPS_WEPS (distance)	TEPS_WEPS (distance,ps)	WEPS (revised)	TEPS_WEPS (distance)	TEPS_WEPS (distance,ps)	WEPS (revised)
918	18.9	9.1	9.6	8.7	9.9	8.3	8
1004	7.6	7.9	8.8	8.7	8.1	9	8.7
1007	13.6	15.4	10.4	10	7.4	10	10
1009	1.5	1.5	0.3	1.5	1.2	1.2	1.5
1106	34	33.1	32.8	33	33.1	33.1	33.2
1109	36.6	27.5	29.4	30.4	27.9	32.2	29.5
1112	45.3	46.2	45.8	45.7	45.8	45	45.6
1115	44.2	45.9	45.8	45.9	45.5	45.6	45.5
1204	33.1	23.3	24.4	24.6	23.2	20.1	24.6
1210	7.5	8.8	9.1	10.4	9.7	9.5	10.4
1215	9.5	13.3	14.6	13.7	13.8	13.6	13.6
1216	11.2	9.6	6	8.3	4.3	5.5	8.8
1217	16.8	4.5	7.1	4.2	4.7	6.7	4.2
1304	2.5	1.4	1.7	1.9	1.9	2.3	2.1
Total	16.9	14.8	11.5	14	14.3	11.3	13.9

Table 6.5 Result of DP and SDP using WEPS and TEPS_WEPS models with damage function

	Damage function using damage in DP		Damage function using damage in DP
Ad hoc operation actually conducted	5	TEPS_WEPS (distance) DP	2.39
Operation under flood control rules regulated in dam operation manual	6.13	TEPS_WEPS (distance)DP (revised)	2.47
DP with perfect forecast	2.24	TEPS_WEPS (distance, ps) DP	2.41
SDP with WEPS	2.31	TEPS_WEPS (distance, ps)DP(revised)	2.41
DP with ensemble mean of WEPS	2.34		

of SDP and DP by using WEPS and TEPS_WEPS model. The figure shows that cities might suffer flood when they conducted operation under flood control rules regulated in dam operation manual and that ad hoc operation which was actually conducted by the dam integrated management offices prevented cities from severe damage by flood. Moreover, the SDP and DP by using WEPS as well as the proposed method would give safe margin of 1.2 m of water level. Unfortunately, the present chapter did not improve flood control by proposing TEPS_WEPS models. However, TEPS_WEPS model gave more frequent updating of the forecast without reducing the accuracy.

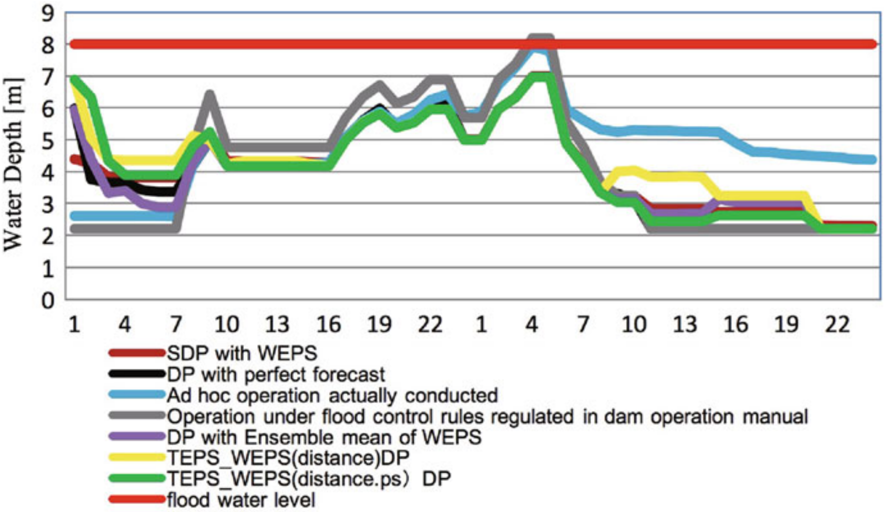

Fig. 6.10 Water level at the evaluating point in the river; *red horizontal line* shows design flood

These appropriate operations made by SDP and DP by using WEPS and TEPS_WEPS models come from the prior releasing of stored water from reservoir which depends on the forecasted amount of water exceeding the dam capacity. Then, the reservoirs had enough space to store flood.

6.5.5 Conclusion

The discussion in the present chapter is summarized into four following topics:

1. Stochastic dynamic programming (SDP) optimization by using ensemble weather forecast decreased the water level at Nabari evaluating point proofing effectiveness of ensemble weather forecast for optimization of dam operation.
2. DP optimization using mean of rainfall amount of ensemble weather forecast exceeded amount of stored water from capacity for flood control.
3. Evaluation of the formulation of cost function suggested that the second order of discharge proposed by Takasao et al. (1982) gave the best optimization.
4. When only dangerously predicted ensemble members were used for optimization, too much amount of water was released to cause the fear of flood at the lower part of the basin.
5. The authors proposed a method which gives highly frequent prediction of rainfall amount when typhoon comes. The method was named as TEPS_WEPS model, and they combined the results of weekly ensemble prediction system (WEPS) and typhoon ensemble prediction system (TEPS). The TEPS_WEPS models produced reasonable forecast of rainfall amount with 6 h updating frequency, whereas WEPS is updated every day.

6. The TEPS_WEPS models have been applied to the same typhoon event as Oishi and Masuda (2013) have dealt with. TEPS_WEPS models reduced water level by 1.2 m from operation under flood control rules regulated in dam operation manual and 0.9 m from ad hoc operation actually conducted by the dam integrated management offices.

These results show the efficiency of the models proposed in the present chapter. For better understanding of the advantage and disadvantage of the model proposed in the present chapter, application of the model into several typhoon events is needed.

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