Improvement of the flood control of a dam in a snowy region using cumulative rainfall forecast

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Abstract This study aims to improve a dam's discharge operation by using rainfall forecasts. First, we compared the accuracy of forecasted cumulative rainfall to that of forecasted time-series rainfall. As a result, the advantage of forecasted cumulative rainfall was ascertained. Next, we examined dam discharge operation in which prior flow and flood control operation were executed based on forecasted cumulative rainfall. The operation was simulated for snowmelt flood events. The proposed operation was found to be effective in improving the flood control capability of the dam.

Keywords flood control; forecasted cumulative rainfall; forecast accuracy; prior flow; snowmelt flood

INTRODUCTION

A major challenge facing multipurpose dams in Japan's snowy regions is flood control during the heavy rains that occur in the snowmelt season, when the flood control capacity of dams tends to be insufficient (Nakatsugawa *et al.*, 2001). Moreover, the Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC) points out that the risk of floods and droughts owing to climate change is expected to increase. Therefore, a strategy to satisfy both flood control safety and water utilization safety needs to be developed. Improving the flood control capability of multipurpose dams will become not only a solution to challenges faced by dams but also a measure for climate change.

This study examined a method of applying rainfall forecast to a dam's discharge operation for the purpose of improving the capability of multipurpose dams. First, the accuracy of forecasted cumulative rainfall was compared with that of forecasted time-series rainfall for the Ishikari River basin, which is in Japan's snowy region. The comparative evaluation based upon the correlation coefficients of observed rainfall and forecasted rainfall indicated that the forecasted cumulative rainfall was more accurate than the forecasted time-series rainfall. In addition, 70% of all observed rainfall was found to fall within the range of 0.7 to 1.8 times the volume of forecasted cumulative rainfall. Next, we examined a discharge procedure on the basis of forecasted cumulative rainfall for Hoheikyo Dam, in Japan. This procedure allowed us to execute prior flow and flood control operation through early analysis of forecasted cumulative rainfall, so that emergency water release could be avoided. The proposed operation was simulated for snowmelt flood events. As a result, emergency water release was found to be avoidable if a parameter equivalent to 1.8 times the volume of forecasted cumulative rainfall was included in the examination. The study further suggests that it is possible to develop operational procedures for dams in snowy regions that do not undermine their water supply function even when their flood control capability is given priority during the snowmelt season.

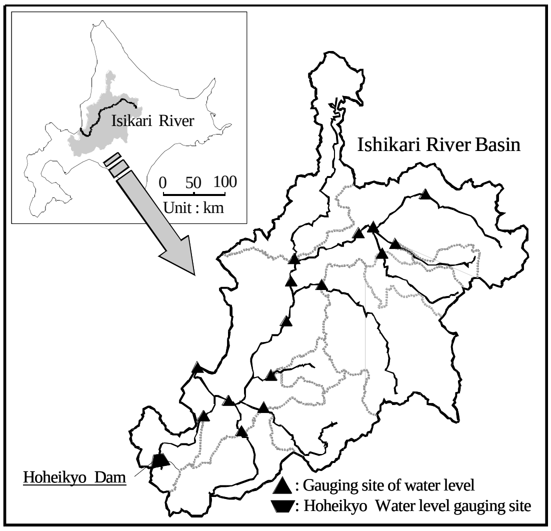

Fig. 1 Study area.

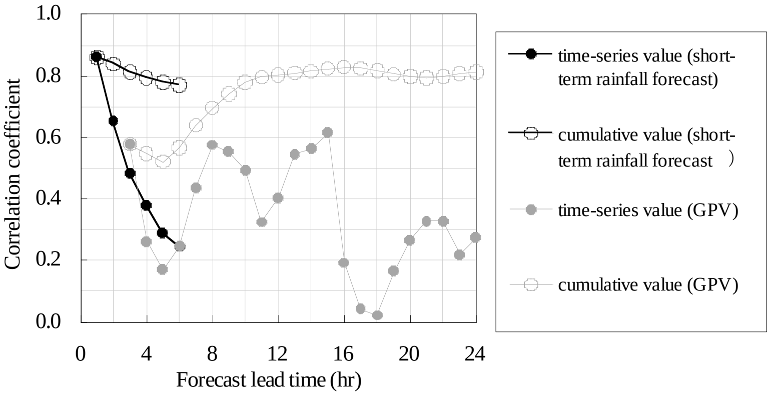

Fig. 2 Relationship between forecast lead time and correlation coefficient.

ACCURACY OF FORECASTED CUMULATIVE RAINFALL

The evaluation of rainfall forecast accuracy was carried out for fifteen stream sections within the Ishikari River basin system (Fig. 1). This analysis used the areal mean rainfall of each stream. The areal mean rainfall was calculated from the following mesh data provided by the Japan Meteorological Agency: short-term rainfall forecast and grid point value (GPV) for the expected hourly rainfall, and radar/raingauge-analyzed precipitation for the observed hourly rainfall.

Fig. 2 shows correlation coefficients of observed rainfall and expected rainfall over the course of the forecast lead times. According to the diagram, the correlation coefficient of forecasted cumulative rainfall was greater than that of forecasted time-series rainfall. The correlation coefficient of forecasted time-series rainfall is likely to decrease with an error in an expected value at each time interval. However, those errors possibly cancel each other out if cumulated. Consequently, it is assumed that the correlation coefficient of forecasted cumulative rainfall was greater than that of forecasted time-series rainfall. In this sense, the forecasted cumulative rainfall can be regarded as more reliable than the forecasted time-series rainfall.

Fig. 3 shows forecasted cumulative rainfall for the next three hours and observed cumulative rainfall. The figure includes a correlation diagram of forecasted values and observed values for cumulative rainfall, and histograms of the observed values. In the

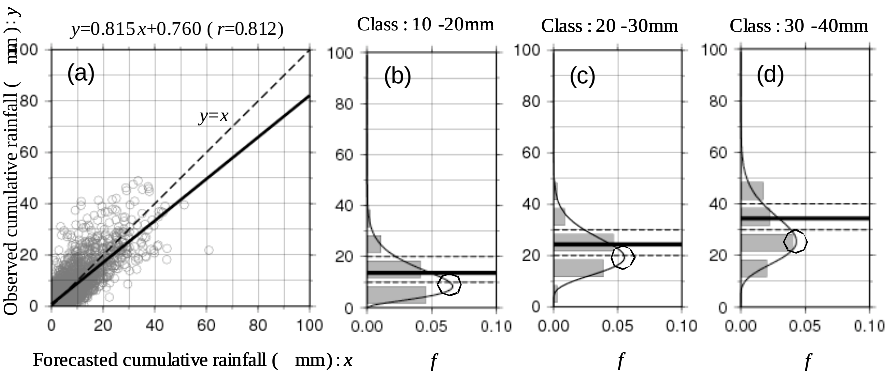

Fig. 3 Distribution of forecasted and observed values of cumulative rainfall (3-hour lead time, based on short-term rainfall forecast). The diagram at left is a correlation diagram of forecasted values and observed values. The three histograms at right indicate observed values in each class of forecasted cumulative rainfall. Between the two broken lines is the class interval width of forecasted cumulative rainfall, and the solid bold line represents the average value for each class.

correlation diagram, the solid bold line represents a regression line between forecasted values and observed values. Three classes of forecasted cumulative rainfall (10 – 20 mm, 20 – 30 mm and 30 – 40 mm) are depicted in the histograms, where the vertical axis refers to observed cumulative rainfall, broken lines indicate the class interval width of forecasted cumulative rainfall, and the bold solid line represents an average value of forecasted cumulative rainfall for each class. The curve in black is a distribution curve of observed cumulative rainfall, which is given by the following equations.

$$f(x)=\frac{\beta^{\alpha}}{\Gamma(\alpha)}x^{\alpha-1}e^{-\beta x} \quad , \quad \alpha=\frac{\mu^2}{\sigma^2} \quad , \quad \beta=\frac{\mu}{\sigma^2} \tag{1}$$

where, $f(x)$: probability density function of Gamma distribution, α : shape parameter, β : scale parameter, μ : average of observed cumulative rainfall each class, and σ^2 : variance of observed cumulative rainfall for each class.

The peak of each curve in Fig. 3 is marked with a circle. The value of x for the peak of each curve satisfies the differentiation equation $f'(x)=0$ derived from Equation (1). And the value of x was calculated by the following equation.

$$x=\frac{\alpha-1}{\beta} \tag{2}$$

Although the correlation coefficient in Fig. 3 exceeds 0.8, the plots are scattered broadly. In the histograms, however, observed rainfall data are distributed with a clear peak, suggesting that errors of forecasted rainfall are insignificant. The class average of forecasted cumulative rainfall (the solid bold line) is greater than the peak of observed cumulative rainfall (the circle). Based on these outcomes, forecasted rainfall in three-hour lead time is slightly greater than the observed value on the whole.

The relationship between the class average of forecasted cumulative rainfall and the mode of observed cumulative rainfall for several lead times is shown in Fig. 4. “LT” in the legend stands for “lead time,” and “LT1” for example means the lead time duration is one hour. According to the diagram, forecasted cumulative rainfall and observed cumulative rainfall have a linear relationship. Short-term rainfall forecast tended to exceed observed values whereas GPV tended to be below observed values.

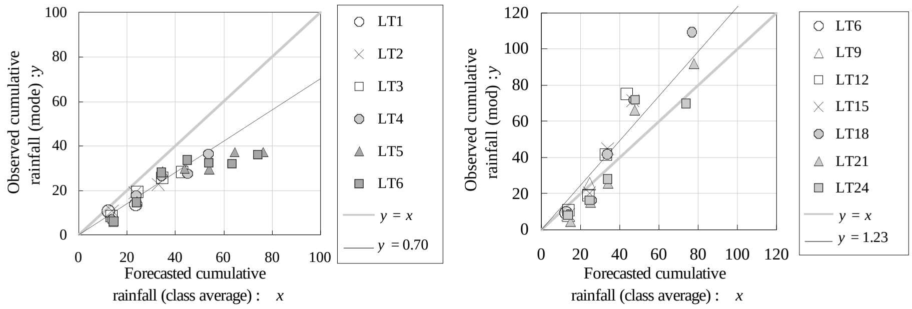

Fig. 4 Forecasted cumulative rainfall and observed cumulative rainfall (left: short-term rainfall, right: GPV).

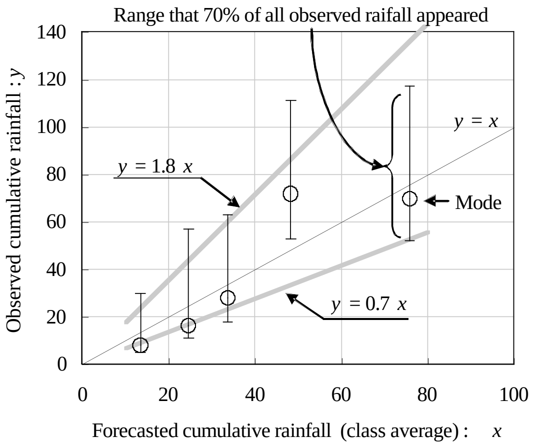

Fig. 5 Range that 70% of all the observed rainfall fell under (24-hour lead time).

Based on the regression line (the solid line in Fig. 4), it is found that 0.7 times the value of short-term rainfall forecast and 1.23 times the value of GPV correspond to the observed value.

Fig.5 shows the range of errors in the forecasted cumulative rainfall for 24-hour lead time. The error range is defined as follows.

$$\int_0^{r_{\max}} f(x) = 0.85 \quad , \quad \int_0^{r_{\min}} f(x) = 0.15 \tag{3}$$

where, $r_{\min}$: the lower value, and $r_{\max}$: the upper value.

According to Fig.5, as the forecast lead time is prolonged, the error range becomes wider. Also, observed cumulative rainfall fell within the range between 0.7 and 1.8 times the volume of forecasted cumulative rainfall with a probability of 70%.

DAM OPERATION USING FORECASTED CUMULATIVE RAINFALL

The necessity of emergency water release was judged by comparing two factors: the volume of dam influent estimated to occur from forecasted cumulative rainfall, and the space available in the dam. The available space V_i and the influent volume Q_i were calculated using the following equations.

$$V_i = (V_{\mathrm{E}} - V_{\mathrm{O}}) + i \times 3600 \times q_{\mathrm{out}} \tag{4}$$

$$Q_i = fAR_i \times 10^3 \tag{5}$$

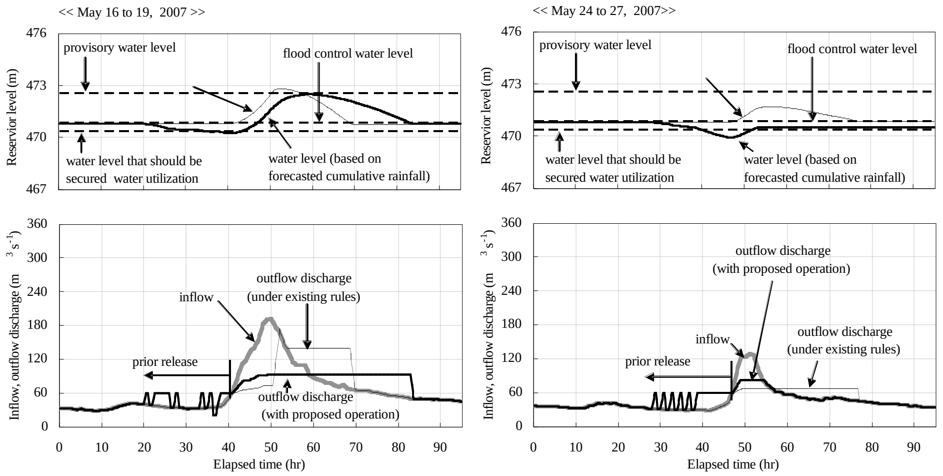

Fig. 6 Simulation results of dam operation.

where, i : forecast lead time (hr), V_i : space available at i hours ahead (m^3), V_0 : volume of water stored at present (m^3), V_E : volume of water stored when emergency release begins (m^3), q_out : outflow discharge at present (m^3 s^{-1}), Q_i : total inflow from present to i hours ahead (m^3), f : runoff percentage, A : catchment area (km^2), and R_i : total rainfall from present to i hours ahead (mm)

The runoff percentage f was assigned the value of 0.82, in reference to the rate of the total outflow to the total rainfall in past flood events. R_i was given a value equivalent to 1.8 times the volume of forecasted rainfall (Fig. 5). The R_i must include the snowmelt, so we calculated it from the observed meteorological data by using a snowmelt model (Usutani *et al.*, 2007).

When the expected volume of dam influent Q_i exceeds the available space V_i, water release is executed by the following rules.

1) Water is released at a rate (60 m^3 s^{-1}) low enough to avoid causing damage to the downstream area, if the inflow is smaller than or equal to the flood discharge (60 m^3 s^{-1}). We allow the reservoir level to fall below that which satisfies the water utilization requirement. This operation is called “prior flow.”
2) The outflow discharge is increased in proportion to the inflow, if the inflow rate exceeds 60 m^3 s^{-1}. The increment of the outflow discharge is assigned 40% of the increment of the inflow. The greatest outflow discharge is the design maximum discharge (140 m^3 s^{-1}).

SIMULATION RESULTS OF DAM OPERATION

The proposed procedure was simulated for two events of snowmelt floods of different scales. The results are shown in Fig. 6. The May 16 event was a large-scale flood that needed emergency water release, whereas the small-scale flood event on May 24 did not need such release. Regarding the May 16 event, a large amount of discharge at a rapid increasing rate would have taken place if the operation of emergency water release had been executed according to the existing rules. With the operation based on the forecasted cumulative rainfall, we were able to avoid emergency release because prior flow started before the dam inflow increased. For the May 24 event, due to prior flow, the reservoir water level remained low by the time inflow would have reached the flood level. This operation seems to be excessive release. However, the water level at the end of the flood satisfied the capacity for water utilization. It is assumed that snowmelt water supplemented the excessive release.

The simulation was carried out using a parameter equivalent to 1.8 times the volume of forecasted rainfall with a priority placed on flood control. The simulation result for the May 24 event suggests the possibility of developing operational procedures for dams in snowy regions where flood control capability is prioritized during the snowmelt season.

CONCLUSIONS

In this study, we examined the accuracy of forecasted cumulative rainfall and simulated its application to dam operation. The forecasted cumulative rainfall proved to be more accurate than the forecasted time-series rainfall. Moreover, it was found that water release operation on the basis of forecasted cumulative rainfall was effective in improving the flood control capability of a dam.

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