Annual Journal of Hydraulic Engineering, JSCE, Vol.53, 2009, February

REAL-TIME DAM OPERATION DURING TYPHOON INVASION USING QUANTITATIVE PRECIPITATION FORECAST

Oliver C. SAAVEDRA V.[1] and Toshio KOIKE[2]

[1]Member of JSCE, Dr. of Eng., Researcher, Department of Civil Engineering, University of Tokyo (Bunkyo-ku, Tokyo 113-8656, Japan)

[2]Member of JSCE, Dr. of Eng., Professor, Department of Civil Engineering, University of Tokyo (Bunkyo-ku, Tokyo 113-8656, Japan)

Tropical cyclones which bring rainfall expected for agriculture might also turn into flood damages. To reduce the damages effectively, a system is proposed to support dam operators in flood control taking advantage of the quantitative precipitation forecast. The spatial variability of the quantitative forecast is captured by a distributed hydrological model with an embedded dam network operation. In order to get the optimal decisions a heuristic algorithm drives the hydrological model evaluating different release combination sets based on stochastic seeding. The error forecast is introduced into the iteration as a weight to the release of each dam. The developed system was applied to the upper Tone River in Japan with three multipurpose reservoirs. The efficiency was evident in reducing the flood peaks and volume downstream. This approach has shown the feasibility to be used as a real-time reference for flood management.

Key Words: *Tone River, Real-time Operation, Flood Forecast, Hydrological Model, Optimization*

1. INTRODUCTION

Real-time dam operation during tropical cyclones, also known as typhoons in South East Asia, is critical to reduce floods downstream and save the water level at the reservoirs for different future demands such as hydro power generation, irrigation and water supply. The experience of dam operators is required additionally to the fixed operation curves to make right decisions within short periods of time. The typical lead-time spans several hours normally with a degree of reliability of the weather forecast. Therefore, the flood control with actual lead-time series might be useful to support the decision making in dam operation using forecast rainfall.

Among all weather variables, rainfall is one of the most difficult to predict at meso-scale. However, through advanced techniques such as downscaling using nested models, a reasonable prediction at basin scale were reported[1),2)] among others. The quantitative forecast was successful fed into distributed hydrological models at different scales[3)]. In addition, it was used weather forecast output to simulate dam operation[4)]. The latter two works did simulation rather than optimization.

The efforts in real-time dam optimization during the 90's and beginning of the 21st century were summarized[5)]. It was pointed out the benefit of emerging heuristic programming models to find the global optima in reservoir operation systems.

Lately it was showed successful coupling of MIKE 11 and Shuffled Complex Evolution (SCE) by optimizing historical operation rule curves of Hoa Binh dam, Vietnam[6)]. The research focused on the trade-off between flood control and hydropower generation. However, it would also be interesting to include forecast data in the real-time operation. Additionally, it was reported an optimization of the reservoir operation scheme for flood control affected by typhoons in Taiwan[7)]. The rainfall forecast was performed at each rain gauge and the error forecast was not considered yet. Different from former studies, the present study attempts to take advantage of quantitative precipitation forecast in real-time dam operation using a coupled distributed hydrological model to a heuristic algorithm. It proposes solving the control problem globally and introducing the error forecast in the iteration scheme defining weights according to its accuracy.

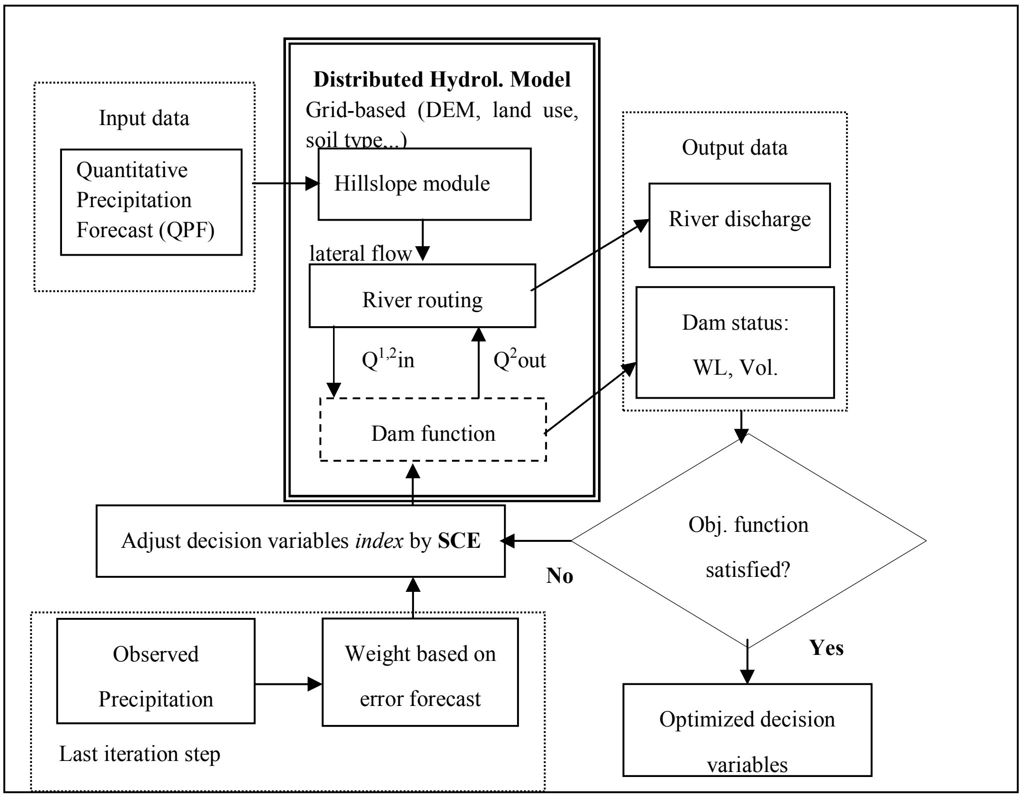

Fig. 1 Overview of proposed system for dam operation using QPF.

2. METHODS

This study employs a physically-based hydrological model namely Geomorphology-Based Hydrological Model (GBHM)[8]. It simulates hydrological processes using governing equations relying in two modules. First, a hillslope module simulates hydrological processes such as canopy, interception, evapo-transpiration, infiltration, surface flow, and subsurface flow, as well as exchanges between groundwater and surface water. Second, the River network routes water using the kinematic wave approach. This simulation sequence is performed at each sub-basin and linked by the Pfafstetter scheme. Moreover, every sub-basin is divided into a number of flow intervals considering the flow distance to the outlet. The flow interval length has been defined as twice the simulation grid size. The hillslope module calculates surface runoff and subsurface flow that become the lateral inflow to the main River channel. The River flow routing module then conducts gathered water from each flow interval from sources to the outlet direction along the main River channel which is lumped within each sub-basin. This procedure dramatically reduces computing time because it is a one-dimensional simulation relying on the geo-morphological properties of the basin. See the double framed box in **Fig. 1**. The stream flow within the river network might be altered by the existing dams. Therefore, a dam function is needed. First, the inflow *Qin* is calculated at upstream flow interval by the GBHM as intake to the dam. A simple storage function approach was used to express the change in volume within a time interval Δt, as the inflow minus outflow from a dam. Then, the reservoir storage at the current time step V_2 can be obtained as:

$$V_2 = V_1 + \left(\left(\frac{Q^1 in + Q^2 in}{2} \right) - Q^2 out \right) \Delta t \qquad (1)$$

where the subscript *1* refers to the last time step. Note that the release $Q^2 out$ is assumed constant between time steps *1* and *2*. Both inflows $Q^{1,2}in$ to the reservoir are provided by the GBHM as in the dashed box of **Fig. 1**. The last time step volume V_1 needs to be set as initial condition. Then, using the h-v curve the water level can be calculated. In conventional dam operation, the release can be calculated using an operational rule. However, during typhoon invasion the release is a function of the potential flood volume and the decision variable which is suggested by the Shuffled Complex Evolution (SCE) [9]. Once the release is defined, flow is routed downstream by the GBHM.

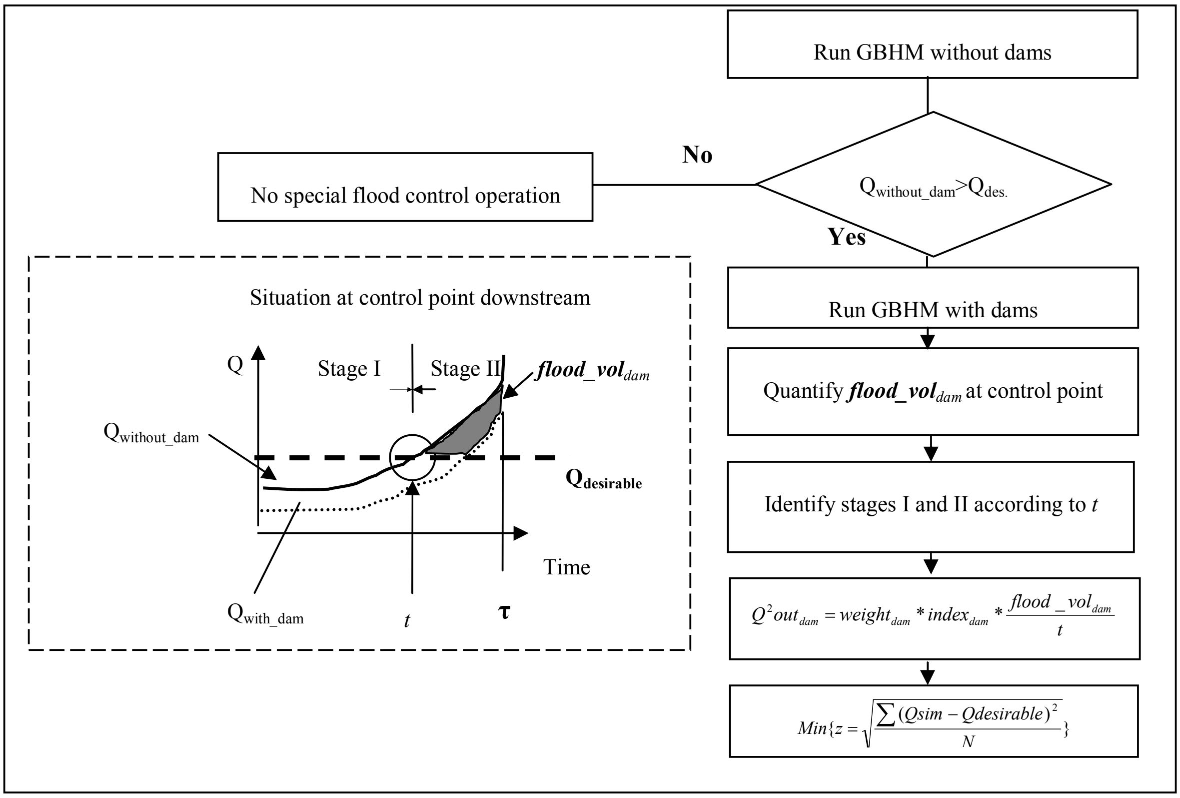

Fig. 2 Objective function for flood control and water use.

The heuristic algorithm SCE which searches for the global optima was chosen. This has being used widely in calibration of hydrological models, but here the application is in dam operation. Then, the SCE drives the GBHM seeding different combination of decision variables into the dam function until the objective function is fulfilled as seen in **Fig. 1**. The objective is to reduce flood peaks downstream and store water at dams for future use. Then, a desirable discharge is defined as the average of the observed values exceeding the mean annual discharge at the control point. It can also be understood as a desirable stream flow expressing flood management and dam purposes during typhoon invasion as:

$$Q_{desirable} = \sum_{i=1}^{N} \frac{Q_i}{N}; \qquad Q_i > Q_{annual\_mean} \qquad (2)$$

Actually, the system is activated when the simulated discharge surpasses the threshold without dam effect as seen in upper part of **Fig. 2**. The procedure is also summarized by the flowchart in right hand side. First, the GBHM is run to simulate discharge downstream without the dam effect, $Q_{without\_dam}$. If this value does not exceed the desirable discharge $Q_{desirable}$, the system is not activated. Otherwise, the simulated discharge downstream with the dam effect Q_{with_dam} needs to be calculated, assuming the initial water level of each dam to their minimum. The potential flood volume $flood\_vol_{dam}$ to be reduced is then quantified as the integrative volume between the simulated discharge curves $Q_{without\_dam}$ and Q_{with_dam} while both exceed $Q_{desirable}$ as seen in the left part of **Fig. 2**. The magnitude of $flood\_vol_{dam}$ represents the total inflow to the dams which might cause a flooding at protecting point. The intersection of $Q_{without\_dam}$ and $Q_{desirable}$ identifies stages I and II according to *t*. The system is expected to release water Q^2_{out} during stage I to leave enough flood control volume. Once stage II is reached, the gates are closed partial or totally in order to replenish water at reservoirs while the optimization horizon τ lasts. This last value will match the lead-time, unless the simulated discharge is lower than $Q_{desirable}$. The magnitude of Q^2_{out} is a function of $flood\_vol_{dam}$, decision variable and the error forecast weighting. The objective function to be solved by SCE is proposed to minimize z as a function of the simulated and desirable discharge at protecting point as seen at the bottom part of **Fig. 2**.

The decision variables $index_{dam}$ are the release-flood volume ratios. The upper boundary of the decision variables are defined as the maximum ratio which is one. The lower boundary is set to zero meaning the gates are completely closed.

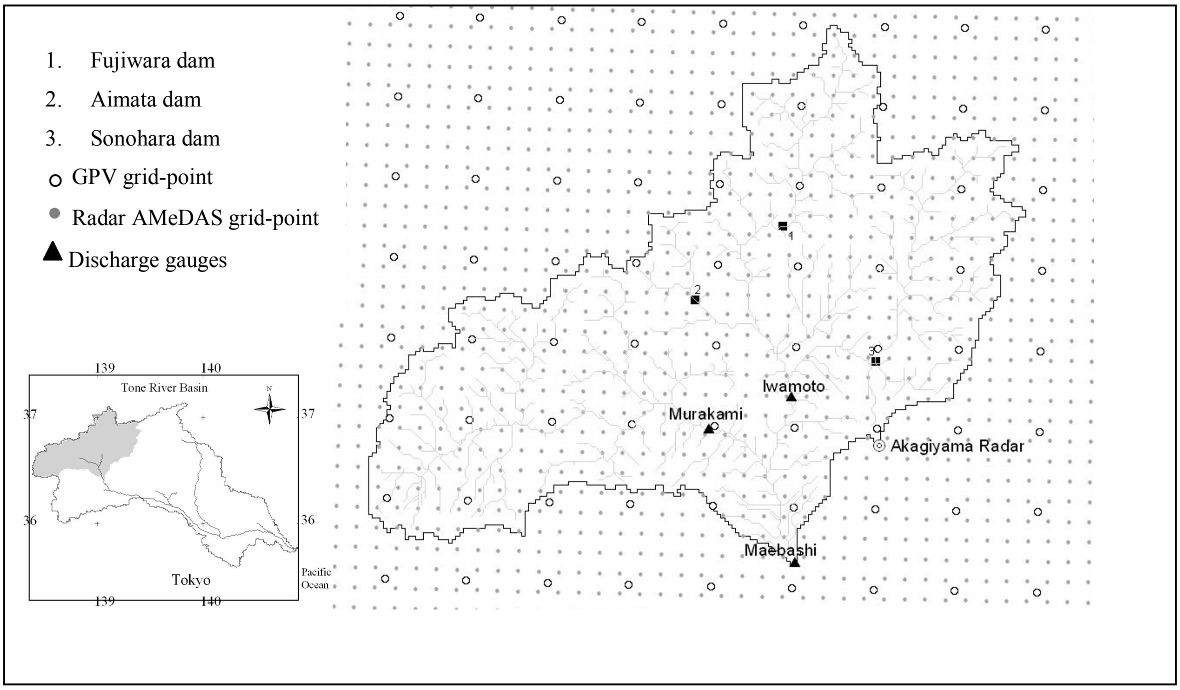

Fig. 3 Location of dams and discharge gauges in the study area.

The weight for each dam is proposed to be a function of the standard deviation obtained from the error forecast averaged over the contributing area to each dam as:

$$weight_{dam} = 1 \pm \frac{\sigma_{error\_forecast}}{10} \qquad (3)$$

The error forecast is defined as the difference between a forecast and the actual observed value from last time step iteration. In this study the standard deviation was selected to express how spread the error forecast is within the optimization horizon. In this fashion, it is expected that lower values of standard deviation (more accurate forecasts) affect the release less and vice versa. Moreover, the over and underestimation of forecast, taken from the average bias, will decide a decrease or increase respectively. As the forecast gets better the weight will get closer one. In short, it is expected that the weights reflect the accuracy of last time step's QPF and attempts to compensate at current optimization step.

3. APPLICATION

The upper Tone River basin, our target area, is located in the northern headwaters of the Tone River basin, in the Kanto region of Japan, as indicated in gray on the left side of **Fig. 3**. The Tone River is a very important source of water supply, irrigation and power generation for the Tokyo Metropolitan area and surroundings. Therefore, its management is crucial for the region. A delineated basin area of 3300 km^2 was defined down to the Maebashi discharge gauge as seen in **Fig. 3**. The main River channel flows north to south. The elevation varies from 100 to about 2500 m and the mean is about 1020 m. The long-term average precipitation is about 1500 mm per year. In addition, heavy rainfalls events occur from July to October and are commonly associated with typhoons and seasonal front activities. Particularly, typhoons bring the highest heavy rainfall such as the one recorded in the region took place in September 1947 with 171 mm within 3 days caused by typhoon Catherine, resulting in catastrophic flooding with 1.6 million people affected. At that event, the flooding area also included Tokyo metropolitan area since the embankment was broken.

Two former works[10), 11)] simulated independently dam release of two sub-basins of upper Tone River using interpretation of observed weather radar products. The present application besides integrating both areas focuses on real-time operation using quantitative precipitation forecast in order to forecast optimal dam release schedules.

The hydrological model was set-up using 50 m resolution Digital Elevation Model (DEM) which was aggregated into 500 m grid. Additionally, land use, soil type and geological maps were prepared for the study area using Geographic Information System (GIS). A 100 m resolution land use data available for the region was classified into 6 categories. Among them, forest and grasslands were the most dominant representing 79.3 % and 9.5 % of the total

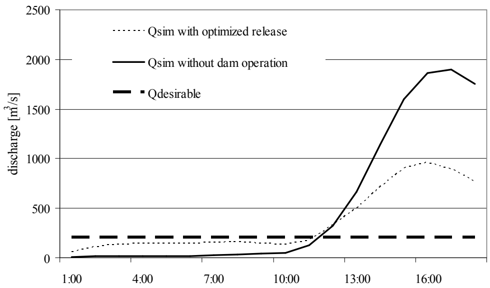

Fig. 4 Flood reduction using 18-h GPV issued at 00:00 on 10 July 2002 at Iwamoto gauging station

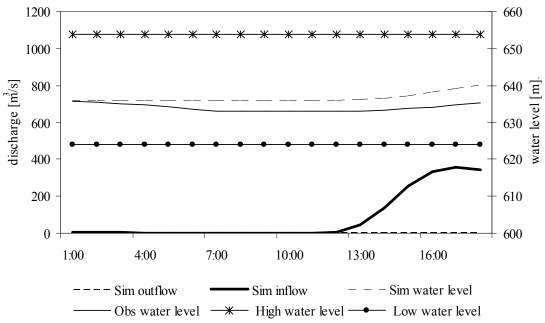

Fig. 5 Fujiwara dam's status

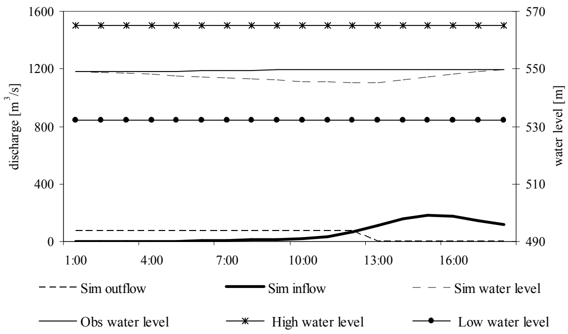

Fig. 6 Aimata dam's status

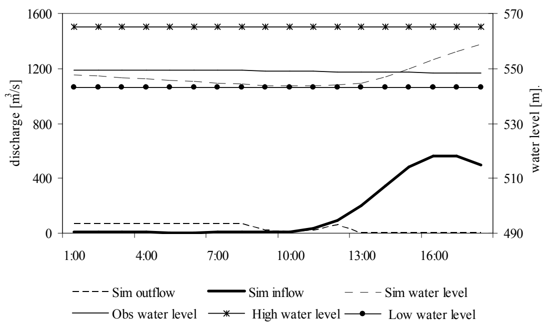

Fig. 7 Sonohara dam's status

area respectively. Thematic maps such as surface terrain slope, topsoil depth, and hillslope length were then derived from the basic data above using GIS. The observed radar products calibrated with rain gauge was obtained from Automated Meteorological Data Acquisition System (AMeDAS) and delineated to the study area. The temporal resolution is 1 hour at 2.5 km.

The Meso-Scale Model (MSM) weather forecast provides, among other weather variables, a quantitative precipitation namely Grid Point Value (GPV) at 0.125º spatial resolution, as seen in circles in **Fig. 3**, is issued every 6 h with 18 h lead-time. The data set covers all Japan and it is archived from 1 July 2002. The MSM-GPV data is produced by the Japan Meteorological Agency (JMA) and it can be accessed at the University of Tokyo' site: http://gpv.tkl.iis.u-tokyo.ac.jp/GPV/. As a reference the latter site also archives global forecast at 1.25º resolution issued over 12 h at different lead-times.

4. RESULTS AND DISCUSSION

The objective of this application was to examine the effectiveness of the proposed system in optimal dam operation targeting typhoon # 6 causing a flood event 8-12 July 2002. Model parameters were calibrated by minimizing the difference between observed and simulated discharges at gauges. The RMSE error was chosen to focus in the peaks of the hydrographs during rainy season 2001. In decreasing order of sensitivity: the saturated hydraulic conductivity, volumetric soil moisture, soil anisotropic and maximum surface storage were calibrated for each soil and land use type.

The hydrological model runs at 1 h time step while the optimization horizon at 18 h to match the lead-time forecast. The initial condition of runoff, soil moisture and groundwater is updated over 6 h using available observed radar products from recent measurements. Three dams arranged in parallel namely Fujiwara, Aimata and Sonohara were selected to reduce floods at Iwamoto gauging station as seen in **Fig. 2**. An example of the system's response is shown in **Fig. 4** which indicates flood peak reduction at the control point. The early release from the three dams is evident to increase the flood control capacities as seen at the bottom of **Figs. 5, 6 and 7**. Generally, during the flood peak, after 13:00, the gates are closed to fulfill the requirement of the objective function. This kind of flushing is typical during typhoon season as a preparedness measure for the upcoming flood event. The objective function using QPF also encourages storing water at reservoirs for future usage by 1) setting the upper boundary of the decision variables to the total flood volume forecasted downstream and 2) the total release can not to exceed the total inflow forecast within the optimization horizon. At the end of each simulation period, the water levels of the three dams were almost replenished or higher than their initial levels as seen in continuous line at the upper right of **Figs. 5, 6 and 7**.

Table 1 Summary of optimal release calculation using 18-h GPV issued at 00:00 on 10 July 2002

Dam name	Std. deviation	Weight	Decision variable	Flood volume [Mm^3]	Optim. release [m^3/s]
Fujiwara	0.0607	1.006	0.0026	4.97	0.30
Aimata	0.1117	1.011	0.8197	3.78	72.42
Sonohara	0.4156	1.042	0.3075	8.69	64.42

A sharp increase of water level can be noticed in **Fig. 7** since Sonohara dam has the smallest capacity and the largest contributing area. Then, in the event that it reaches high water level, "free flow" prevails rather than the suggested release. Accounting the total volume stored at three reservoirs, the present system showed a surplus by comparing to the volume stored using the observed release. This is a clear advantage of choosing the flood volume as a magnitude to solve the allocation problem rather than the flood peak alone.

The standard deviation of the error forecast and the weight introduced in the iteration are summarized in **Table 1**. The evaluation of different weights for each dam was carried out to highlight the importance to use a distributed hydrological model to show the pattern of the QPF within the basin. In this particular application the weight affected a sort of conservatively due to the accuracy of QPF; however, this might not always be the case. Then, the ratio could be adjusted according to the most recent accuracy of QPF.

5. CONCLUSION & OUTLOOK

It can be concluded that the proposed real-time reservoir operation system is able to take advantage of the quantitative precipitation forecast using grid-point values. The system couples a distributed hydrological model with an optimization algorithm. A weight using the statistics of the error forecast within the contributing area is proposed to be included in the iteration process. The suggested objective function was able to reduce flood effects downstream and also increase the total volume at the reservoirs. Then, the system has shown feasibility to support dam operators as a real-time reference tool. This type of real-time operation is needed in humid mountain and highly vegetated basins, like in Japan, Taiwan, and Vietnam attacked by typhoons.

Besides the results of the flood event showed, it was analyzed 4 other events. The five cases were evaluated and found very good, 3 out 5, good in one case, and fair in another case. To improve system's performance in event-by-event basis, Kalman filtering technique and the analysis of the rainfall in a wider region might be very useful.

ACKNOWLEDGMENT: We would like to thank the River Bureau of the Ministry of Land, Infrastructure, Transportation and Tourism of Japan for providing valuable information regarding the operation of dams and the discharge data in the Tone River.

REFERENCES

1) Krzysztofowicz, R., and Collier, C. G.: Quantitative precipitation forecasting II, *Journal of Hydrology*, Vol. 288, Issues 1-2, pp. 1-236, 2004.
2) Golding, B.W.: Quantitative precipitation forecasting in the UK, *Journal of Hydrology*, Vol. 239, pp. 286-305, 2000.
3) Jasper, K., Gurtz, J., and Lang, H.: Advanced flood forecasting in Alpine watersheds by coupling meteorological observations and forecasts with a distributed hydrological model, *Journal of Hydrology*, Vol. 267, pp. 40-52, 2002.
4) Collischonn, W., Hass, R., Andreolli, I., and Morelli Tucci, C.E.: Forecasting River Uruguay flow using rainfall forecasts from a regional weather-prediction model, *Journal of Hydrology*, Vol. 305, pp. 87-98, 2005.
5) Labadie, J. W.: Optimal Operation of Multireservoir Systems State-of-the-Art Review, *Journal of Water Resources Planning and Management*, ASCE, Vol. 130(2), pp. 93-111, 2004.
6) Ngo, L.L., Madsen, H. and Rosbjerg, D.: Simulation and optimisation modelling approach for operation of the Hoa Binh reservoir, Vietnam. *Journal of Hydrology*, Vol. 336, pp.269-281, 2007.
7) Hsu, N.-S. and Wei, C.-C.: A multipurpose reservoir real-time operation model for flood control during typhoon invasion, *Journal of Hydrology*, Vol. 336, pp. 282-293, 2007.
8) Yang, D., Herath, S., Musiake, K.: Hillslope-based hydrological model using catchment area and width functions, *Hydrological Sciences Journal*, Vol. 47, pp.49-65, 2002.
9) Duan, Q., Sorooshian, S., and Gupta, V.K.: Effective and Efficient Global Optimization for Conceptual Rainfall-Runoff Models. *Water Resources Research*, Vol. 28(4), pp. 1015-1031, 1992.
10) Yang, D., Koike, T., and Tanizawa, H.: Application of a distributed hydrological model and weather radar observations for flood management, *Hydrological Processes*, Vol. 18, pp.3119-3132, 2004.
11) Saavedra, O., Koike, T. and Yang, D.: Application of a distributed hydrological model coupled with dam operation for flood control purposes. *Annual Journal Hydraulic Engineering*, Japan Society of Civil Engineers JSCE, Vol. 50, pp. 61-66, 2006.

(Received September 30, 2008)