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Development of a real-time distributed flood prediction system in a flow regulated river basin

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Abstract: A real-time distributed flood prediction system (RDFPS) is developed for the Yodo River basin (7,281 km^2) in Japan. The system predicts river discharges at 1,707 locations along the river channel network. It predicts also inflows, outflows and water levels of eight multi-purpose dams located in the basin. A distributed hydrologic model used for this system is composed of 1) distributed rainfall-runoff models with 250 m resolution, 2) kinematic wave river routing models, and 3) dam operation models. Rainfall forecasts used for driving the simulation model have six hours of the lead time with 2.5 km resolution (5 km resolution for three to six hours of lead time). The performance of the developed system is presented here with the initial results of a hindcast for a flooding event in September 2004.

1. Introduction

Steep mountainous landscapes and wet climate conditions in Japan feature the vulnerability to a flash flood, which is extremely dangerous because of its sudden nature. In 2004, for example, a series of severe flash floods killed more than 230 people in Japan. A noticeable feature of the disasters was the concentrations of their damages in tributary river basins, where the flood safety levels are relatively low due to fewer investments on river works and no flood control by dam reservoirs. In addition, not enough information associated with river discharge is available for issuing accurate flood warnings or for taking relevant counter measures.

Recent advances in numerical weather forecast and hydrologic simulation techniques with a distributed parameter model may enable significant improvement to predict flash floods. More accurate and finer flood predictions in terms of magnitudes, locations, and timings, compared to current operational ones with a lumped parameter model may be possible by converging state-of-the-art technologies in hydrology, meteorology and computer sciences. In this study, we develop a real-time distributed flood prediction system in the Yodo River basin with aims at constructing a robust system conducting data acquisitions, simulations, predictions, data storing, and interactive displaying of predicted results.

2. A distributed hydrologic model incorporating dam operation models

2.1 Study area

The study area of this research is the Yodo River basin in Japan. The total area of the Yodo River basin (upper Hirakata) is 7,281 km^2 (Fig. 1). The origin of the Yodo River is Lake Biwa (670 km2), whose catchment area is 3,848 (km^2). The outflow of from Lake

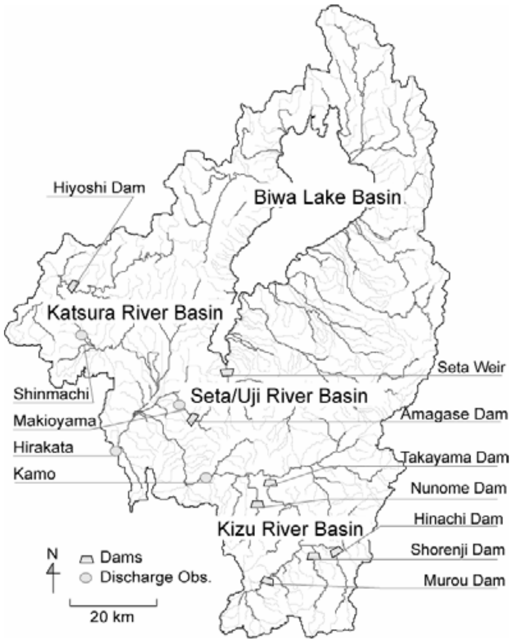

Fig. 1 Map of the Yodo River basin

Biwa is controlled by Seta weir and flows into the Uji River, whose catchment area is 506 km^2. The Uji River runs through Amagase dam and joins the Kizu River and the Katsura River. The Kizu River basin (1,596 km^2) has five multi-purpose dams including Takayama dam, and the Katsura River basin (1,100 km^2) has one multi-purpose dam called Hiyoshi dam. The lower main Yodo River flows from the confluence of the three rivers and it flows into Osaka bay through Hirakata. The catchment area of the lower main Yodo River (upper Hirakata) is 231 km^2. The mean annual precipitation of the Yodo River basin is about 1,800 mm. The mean annual discharge at Hirakata is 273 m^3/s.

2.2 Structure of the distributed hydrologic model

A distributed hydrologic model for the Yodo River basin is developed (Sayama *et al*. 2005, 2006) based on "Object-oriented Hydrological Modelling System (OHyMoS)". The following three kinds of element models compose the whole structure of the model.

1) River element model: The kinematic wave model is applied to a river segment, which is prepared from digital river channel network data and the location information of Lake Biwa. The length of each river segment is set to be about 3 km.

2) Sub-catchment element model: A digital elevation model with 250 m resolution is used to calculate the flow direction and to delineate a sub-catchment for each river segment. A stage-discharge relationship simulating saturated, unsaturated subsurface and surface rainfall-runoff (Tachikawa *et al*. 2004) is applied to each grid-cell.

Figure 2 (a) shows a schematic diagram of the soil layer of the model. In this figure, the soil depth is D (m), the water depth corresponding to the water content is d_s (m), and the water depth corresponding to maximum water content in the capillary pore is d_c (m). Figure 2 (b) shows the stage-discharge relationship. Let k_c and k_a be saturated hydraulic conductivities in capillary pore and in non-capillary pore, respectively, and $v_c = k_c i$, $v_a = k_a i$ (i: slope), then the relationship between the discharge per unit width q (m^2/s) and the water

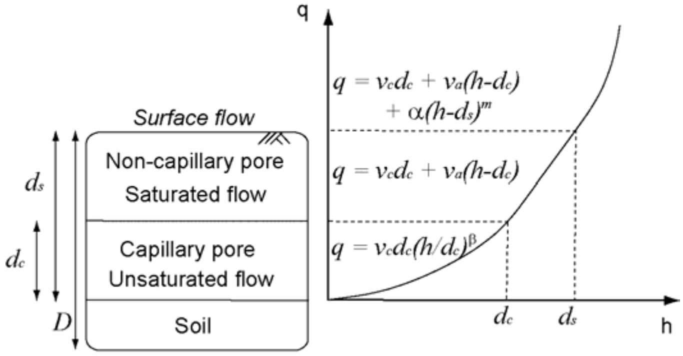

Fig. 2 Schematic diagram of (a) the soil layer and (b) the stage-discharge relationship of saturated-unsaturated subsurface and surface runoff model

depth h (m) is described as follows:

$$q = \begin{cases} v_c d_c \left(\dfrac{h}{d_c} \right)^{\beta}, & (0 \le h \le d_c) \\ v_c d_c + v_a (h - d_c), & (d_c < h \le d_s) \\ v_c d_c + v_a (h - d_c) + \alpha (h - d_s)^m, & (d_s < h) \end{cases}$$

where α equals to $i^{1/2}/n$; n is Manning roughness coefficient ($m^{-1/3}/s^{-1}$). A non dimensional parameter β is introduced to describe the reduction of hydraulic conductivity in capillary pore as the water content decreases. β equals to k_a/k_c so as to keep the continuity of the depth–discharge relationship between the capillary pore and the non-capillary pore layers. Combining this depth−discharge relationship and the continuity equation, we simulate rainfall–runoff from each grid-cell. The water flow is routed until it reaches a river segment.

3) Dam element model: By formulating the dam operation rules and decision-making processes of dam operators, a dam operation model is developed (Ichikawa, 2001). It predicts the outflow and water levels of a dam with the input information of inflow, average rainfall in the dam catchment, and operation status of other related dams. The dam operation model is applied to eight multi-purpose dams in the Yodo River basin.

Although each dam has different operating rules, we can categorize all the flood control operations into the following six common operation processes: Ordinary operation; Operation under flood warning; Preliminary release operation; Peak attenuation operation; Flood release operation; and Post flood operation. Each dam is always under one of the six operations, and we formulate the conditions to shift from one operation to another with if-then equations.

3. Development of a Real-time Distributed Flood Prediction System (RDFPS) with the distributed hydrologic model

3.1 Outline of RDFPS

A Real-time Distributed Flood Prediction System (RDFPS) is developed based on the

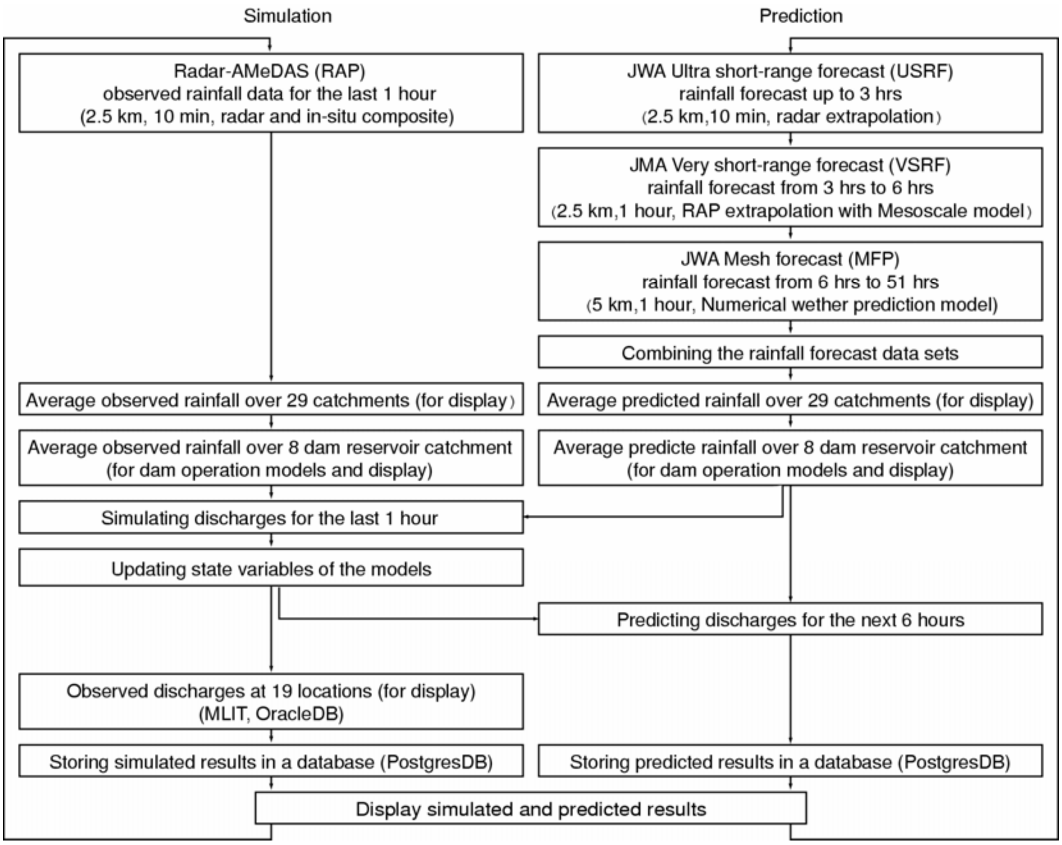

Fig. 3 Flow chart of the real-time flood prediction

distributed hydrologic model for the Yodo River basin. RDFPS predicts river discharges at 1,707 locations in the basin and the reservoir inflows, outflows and water levels at the eight multi purpose dams. It is operated automatically every an hour on a real-time basis to simulate the current river discharges by forcing the model with radar and in-situ composite rainfall data observed in the last an hour. Then RDFPS predicts river discharges for the next six hours by using rainfall forecast. Forecast rainfall is obtained through Meteorological Information Comprehensive Online Service (MICOS) of Japan Weather Agency (JWA). Observed river discharge at nineteen locations and observed dam reservoir inflow, outflow, and water levels at the eight dams are also obtained from a database maintained by Ministry of Land Infrastructure and Transport on a real-time basis. The river discharge data is currently used only to check the simulation performance. The detail of the rainfall data, the procedures, and a visualization system are presented in the following sections.

3.2 Rainfall data used by RDFPS

1) Radar-AMeDAS composite precipitation (RAP): Automated Meteorological Data Acquisition System (AMeDAS) maintained by Japan Meteorological Agency collects precipitation amounts from more than 1,300 in-situ stations at an average interval of 17 km throughout Japan. It is operated every ten minutes on a real-time basis. Weather radar observation network of JMA consists of twenty C-band radars, which are also operated at

ten minute intervals. Radar-AMeDAS composite precipitation (RAP) is used as observed rainfall data to simulate state variables of the distributed hydrologic model for the last an hour. The spatial and temporal resolutions of RAP are 2.5 km and 10 minutes, respectively.

2) JWA Ultra short-range forecast of precipitation (USRF): Ultra short-range forecast of precipitation is issued by Japan Weather Agency (JWA) to provide 10 minute precipitation forecast for the next three hours with 2.5 km resolution. The forecast algorithm is based on a radar extrapolation. RDFPS uses this data to run the hydrologic model for the next three hours.

3) JMA Very short-range forecast of precipitation (VSRF): A Very short-range forecast of precipitation is issued twice an hour to provide one-hour precipitation forecast for the next six hours with 5 km resolution. This forecast is derived from the combination of the Mesoscale Model (MSM) predictions and the extrapolation of RAP data. RDFPS uses this data to run the hydrologic model from three hour ahead to six hour ahead.

4) JWA Mesh Forecast of Precipitation (MFP): A Mesh Forecast of Precipitation is issued twice a day (at around 3 and 15 o'clock) to provide one-hour precipitation forecast for the next 51 hours with 5 km resolution. This forecast is derived from a numerical weather prediction model operated by JWA. The current version of RDFPS does not use this MFP data and the maximum lead time of the current RDFPS is set to six hours.

3.3 Procedure for the real-time flood prediction

The procedure executed every an hour by RDFPS is illustrated in Fig. 3. The procedure is composed of the following main four steps: processing rainfall data, simulating current conditions, predicting future conditions, and storing simulated and predicted results in a database. The detailed descriptions for each step are given here. For the clear illustration of the procedure, let assume that it is now 10:15 and the current state variables of the hydrologic model represent the conditions at 9:00.

1) Processing rainfall data: RDFPS prepares two sets of rainfall data; one is observed rainfall data from 9:00 to 10:00, and the other one is predicted rainfall data from 10:00 to 16:00. As it is mentioned above, the current version of RDFPS uses RAP data as observed rainfall, and USRF, VSRF as predicted rainfall from 10:00 to 13:00 and from 13:00 to 16:00, respectively.

2) Simulating current conditions: RDFPS updates the state variables from 9:00 to 10:00 with the observed rainfall. It calculates also average rainfall in selected twenty nine sub catchments (among them, observed discharge data are available at the outlets of nineteen catchments). The calculated average rainfall data are used to draw hyetographs with a visualization system that is described below in 3.4. Average rainfalls over dam catchments are also calculated because they are used for running the dam operation models as well as for displaying the hyetographs.

The simulated state variables of the distributed hydrologic model are saved in files to predict river discharge for the next six hours from 10:00 to 16:00 with the predicted rainfall and also to update the state variables from 10:00 to 11:00 with the observed rainfall that will be available in the next time step.

3) Predicting future conditions: Using updated state variables as initial conditions, RDFPS predicts river discharge and dam reservoir inflows, outflows, and water levels for

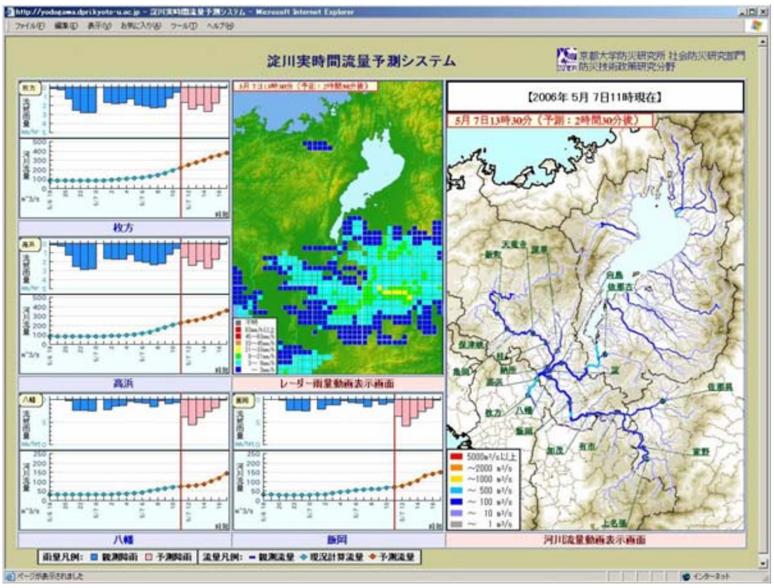

Fig. 4 Flood prediction visualization system

the next six hours (from 10:00 to 16:00). It calculates also predicted average rainfall over the twenty-nine catchments and the dam reservoir catchments.

4) Storing simulated and predicted results in a database: Simulated and predicted results are stored in a relational database, which is accessed by the visualization system. The following items are stored with an hour time step interval.

- Observed discharge at nineteen locations
- Observed average rainfall over twenty-nine catchments
- Predicted average rainfall over twenty-nine catchments (1, 2, …, 6 hours lead time)
- Simulated discharge at twenty-nine locations
- Predicted discharge at twenty-nine locations (1, 2, …, 6 hours lead time)
- Simulated discharge at 1,707 locations
- Predicted discharge at 1,707 locations (1, 2, …, 6 hours lead time)
- Observed inflows, outflows, water tables at the eight dams
- Simulated inflows, outflows, water tables at the eight dams
- Predicted inflows, outflows, water tables at the eight dams (1, 2, …, 6 hours lead time)

All the tables of the database have year, month, day, hour, and through time in second from the beginning of a year. The time represents observed, simulated, predicted “target” time, for example, a six hour-ahead prediction obtained at 10:15 will be stored in the table of six hour lead time, and the time appeared in the table will be 16:00.

3.4 Flood prediction visualization system

We developed an interactive visualization system to view the prediction results through the Internet. The contents of the visualization system are 1) the animation of current and predicted rainfall and discharge distribution maps, 2) predicted hyetographs and hydrographs at the selected nineteen locations as well as at the eight dams. In additions to the interactive visualization system, we developed an automatic renewal visualization system, which is illustrated in Fig. 4. It shows the current and the next six hours

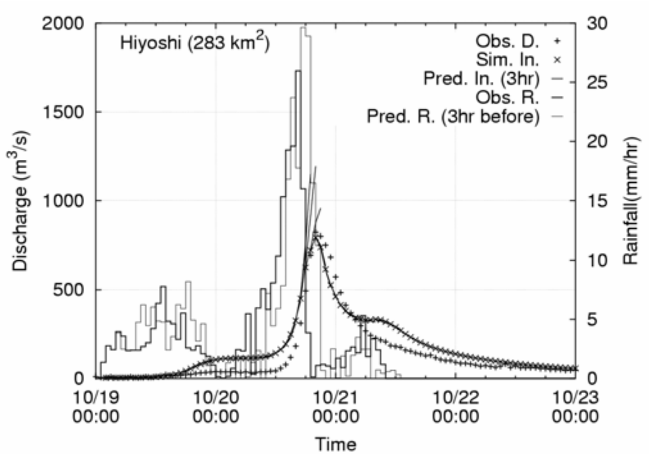

Fig. 5 Hindcast results at Hiyoshi dam (Oct. 19 – 23, 2004)

distributions of rainfall and discharge as well as hyetographs and hydrographs at the nineteen locations automatically.

4. Hindcast results with a flooding event in 2004

In order to investigate the performance of the developed system, we conducted a hindcast for a large flood event caused by typhoon 23rd in 2004. During this typhoon event, a severe storm was observed in the Yodo River basin, particularly in the Katsura River basin. The total rainfall amount in the Hiyoshi dam catchment located in the Katsura River basin was 255 mm for the three days from October 19 to 21. Although the presented results here are not obtained on a real-time basis since the actual operation of RDFPS was started in April 2006, the conditions used here for this hindcast are the same as those used for the real-time operation. Only a difference between this and the real-time operation is that the prediction time horizon is limited up to three hours ahead in this hindcast since VSRF data was not available for the period. The used rainfall data, therefore, are only RAP and USRF.

Figure 5 shows the observed and calculated hyetographs and inflows at Hiyoshi dam. The hyetograph with the thicker line shows the rainfall from RAP, while the hyetograph with the thinner line shows three hours ahead forecast from USRF. Simulated hydrograph with RAP data reproduces the observed inflow reasonably, while the predicted peak discharge with USRF is overestimated compared to the observed discharge due to the overestimation in the rainfall forecast of USRF.

Figure 6 shows the simulated results at Kamo, which is located at the downstream of the Kizu River basin. The total rainfall amount over the Kamo catchment was 181 mm. There is a discrepancy between simulated and observed peak discharges with the relative error of 0.21. In addition, more significant discrepancy was found between the observed and forecasted rainfalls. However, in spite of this significant error in the rainfall forecast, the three hours-ahead discharge prediction with USRF data and the simulated discharge with RAP data are close with the relative peak error of 0.07. It implies that a predicted discharge whose catchment area is larger than a thousand square km is less sensitive to the errors in rainfall forecast and depends more on the hydrologic simulations.

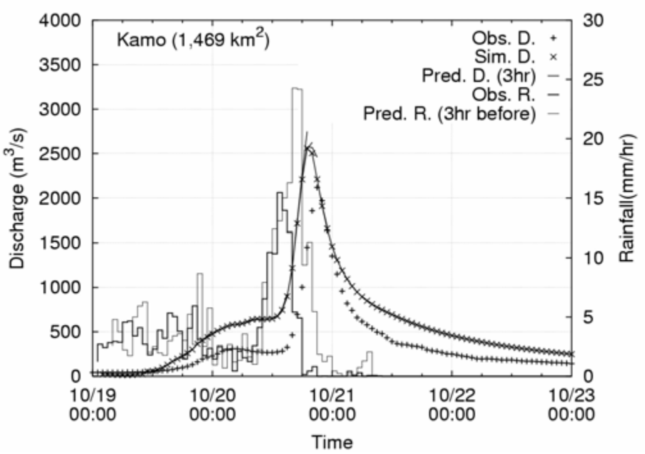

Fig. 6 Hindcast results at Kamo (Oct. 19 – 23, 2004)

5. Conclusions

This paper presented the development of a real-time distributed flood prediction system (RDFPS), which uses a distributed hydrologic model incorporating dam operation models. Using radar in-situ composite rainfall data observed in the latest an hour, the model updates the state variables representing soil moisture distributions, river discharges, and dam reservoirs' conditions. The updated state variables are used as initial conditions of the model to predict future conditions with rainfall forecast of six hours lead time. Simulated and predicted results are stored in a database, so that the visualization system can readily access to the simulated and predicted results. The hindcast test with a typhoon event in 2004 indicates the predictability of large scale flood events.

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