MULTI-RESERVOIR OPERATION USING A DISTRIBUTED BIOSPHERE HYDROLOGICAL MODEL

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According to the fourth IPCC's assessment report, flood damages due to heavy rainfall events are expected to increase. In order to reduce those damages, an integrated dam management becomes a crucial issue. The present study attempts to support dam operators in flood control using meso-scale quantitative precipitation forecast. The spatial variability of the forcing data is captured by a distributed biosphere hydrological model with an embedded dam network operation. The developed system was applied to the upper Tone reservoir system with three existing dams. Additionally, the effect of Yamba dam operation (i.e. nowadays under construction) was simulated. The results indicate that further flood peak reduction is possible using joint operation without sacrificing the storage volume. The usage of distributed biosphere hydrological models seems to be the pathway to a closer interaction with regional atmospheric models.

Key Words: *Tone River, Dam Operation, Yamba dam, Flood Forecast, Biosphere Hydrological Model*

1. INTRODUCTION

Flood hazards are very likely to be intensified due to the global warming according to the fourth assessment report of the Intergovernmental Panel on Climate Change(IPCC)[1]. Heavy rainfall causing floods can be attributed to large water cycle variations at global and regional scales, while flood damages occur at basin scale. The frequency of these events has increased over most land areas, consistent with increases of atmospheric water vapor.

The conventional physical approach to simulate flood events is the usage of distributed hydrological models. They are capable to assimilate rainfall patterns and estimate fluxes like river discharge at selected points, spatial distribution of soil moisture content, evaporation and transpiration. A proper initial soil moisture condition and estimation of evapo-transpiration are crucial for flood forecast. Actually, the energy transfer between land surface and lower atmosphere is neglected by the hydrological models[2]. However, land surface models focus on this energy transfer in the vertical direction.

The recent generation of land surface models describes the vegetation effect with a realistic canopy photosynthesis-conductance. They are key components to improve atmospheric Global Circulation Models (GCM). This generation of land surface models is able to describe the heat transfer and CO_2 assimilation physically-based. However, they simplify the water movement; actually, it is considered only in the vertical axis. Then, it makes sense to combine both models to improve the water and energy cycles representation within a basin which can eventually improve the simulation of high and low flow conditions. A very well known land surface model so-called Simple biosphere model (SiB2)[3] was embedded to a geomorphology-based hydrological model GBHM[4] coming up with a Water and Energy Budget-based Distributed Hydrological Model (WEB-DHM)[5]. The advantages of the coupled model over the

GBHM alone were showed at affordable computing cost[6]. Also a consistent study using satellite products showed the benefits of using the coupled model[7]. However, the dam operation function was not included yet in the new distributed biosphere hydrological model.

A flood peak can be effectively reduced by appropriate dam operation. Optimal release systems to assist dam operators using hydrological models can be found in the literature review[8]. Recent works focused on the optimal rule curves[9] while others in real-time forecast fashion[10],[11],[12]. The present study deals with real-time forecast, but different from aforementioned ones, employs a distributed biosphere hydrological model with embedded dam operation and coupled to a heuristic algorithm to support release instructions. The approach is applied to the upper Tone reservoir system, one of the most important rivers in Japan. The basin has being going through land development, so water and energy demand increased. To achieve effective flood control in the Tone River not only building new structures is important, but also their proper management[13]. The integrated dam operation is also expected[14]. Then, the application here focuses on the joint operation of existing dams and the effect of Yamba dam (i.e. under construction) expecting flood reduction down stream and also store water at reservoirs.

2. METHODS

This study attempts to use the meso-scale atmospheric model output in order to contribute to societal benefits at basin scale as seen the left path in **Fig. 1.** It employs the distributed biosphere hydrological model WEB-DHM, already tested with success in the Little Washita basin, Oklahoma[5] and the upper Tone River in Japan[7]. The model demonstrated the ability to reproduce point-scale energy fluxes, CO_2 flux, and river discharges. Moreover, the model showed the ability to predict the basin-scale surface soil moisture evolution in a spatially distributed fashion. Actually, WEB-DHM couples the SiB2 with advanced physics, and the grid-based GBHM with physical water movement description. At each model grid one combination of land use type and soil type, the SiB2 sub-model is used to calculate turbulent fluxes between the lower atmosphere and land surface independently. The SiB2 updates surface runoff and subsurface flow that become the lateral inflow to the main river channel. Then, the GBHM sub-model is used to conduct the water flow within the river network using one-dimensional kinematic wave equations. The river discharge down stream might be altered by upper dams according to their operation. Then, a dam function is needed to simulate their effect. A mass balance approach was used to express the change in volume as the inflow minus dam release[11]. The inflows to the dams are simulated by the WEB-DHM.

In conventional dam operation, the release can be calculated using an operational rule curve. However, during heavy rainfall the release is suggested by a heuristic algorithm namely Shuffled Complex Evolution (SCE)[15]. Once the release is defined, flow is routed downstream by the GBHM. The SCE algorithm drives the WEB-DHM seeding different combination of decision variables until the objective function is fulfilled[11]. The system is expected to come up with the suggested release schedule within the issuance interval as shown in **Fig. 1**.

Here, the target is to minimize Z defined as the flood peak at the control point down- stream, Vol_flood, and the available free volume at dams Vol_free_dams (i.e. maximum volume minus updated one) as:

$$Z = Vol\_flood + \sum Vol\_free\_dams \qquad (1)$$

Then, the trade-off is done in terms of water volume at the control point versus stored water at the reservoirs useful for water-use.
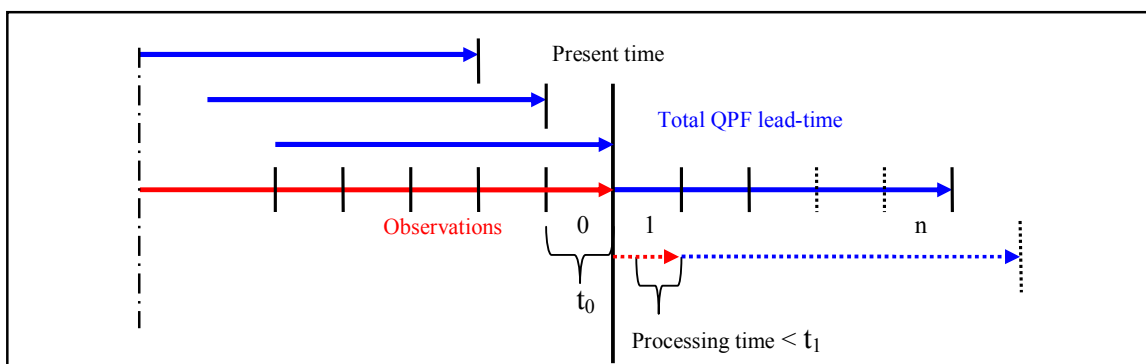

Fig. 1 Overview of the time framework in real-time operation

The decision variables are the release of the dams. Their initial values are obtained by a single a-priori release of each dam according to its capability to reduce potential flood volume[11] at the control point.

The forecast error is defined as the ratio of the forecast to the observed rainfall. The intensity is averaged over the drainage areas to the dams. Then, the ratios are normalized to the highest error value. In this fashion the most inaccurate will be assigned "1" meaning 100 % of a-priori release range which represents the total feasible space of the release. It is expected that for lower magnitudes of weight (more accurate forecasts) the feasible space is narrowed. In summary, the weights show the inaccuracy of previous time step's Quantitative Precipitation Forecast (QPF) limiting the upper and lower boundaries of the present release.

3. APPLICATION

The northern headwaters of the Tone River basin are located about 130 km North-West from Tokyo as displayed at upper **Fig. 2**. 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. The delineated watershed with the location of reservoirs can be seen at bottom of **Fig. 2**. 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. This catastrophic flood affected about 1.6 million people. At that event, the flooding area also included Tokyo metropolitan area since the embankment was broken. After this event, emphasis was made on the development of upper reservoir system as well as embankment improvements at middle and lower reaches. Also, it began the plan to build Yamba dam. Previous studies on upper the Tone River reservoir system focused on Okutone[14] and Agatsuma[16] sub-basins using interpretation of observed weather radar products. Recent efforts integrated both sub-basins using WEB-DHM without QPF[7] and GBHM with QPF[11]. The present application besides merging both areas using WEB-DHM forced by QPF implements the dam functions in real-time operation to get optimal dam release instructions.

1. Fujiwara (12%)

2. Aimata (3%)

3. Sonohara (15%)

4. Yamba (21%)
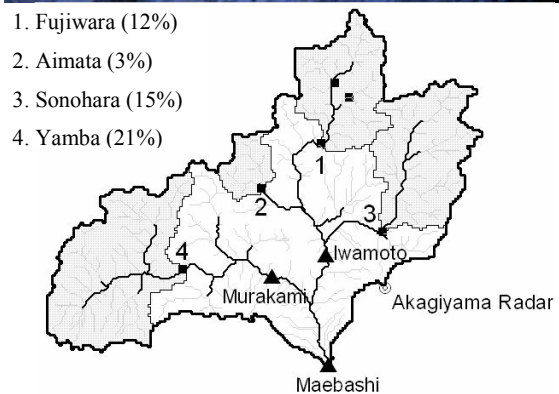
Fig. 2 The studied reservoir system comprises 3304 km^2

The geomorphology was obtained 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. Land use data was reclassified according to the pre-defined SiB2 categories, where broadleaf-deciduous trees were found to be the dominant type in the basin.

Thematic maps such as surface terrain slope, topsoil depth, and hillslope length were then derived from the basic data above using Geographic Information System (GIS). The dynamic vegetation parameters such as Leaf Area Index (LAI), Fraction of Photo synthetically Active Radiation (FPAR) were obtained from satellite data. The air temperature, wind speed, and sunshine duration were obtained from available meteorological sites from Automated Meteorological Data Acquisition System (AMeDAS). Relative humidity and air pressure were obtained from three radiation stations maintained by the Japan Meteorological Agency (JMA). Downward solar radiation was estimated from sunshine duration, temperature, and humidity.

Longwave radiation was then estimated from temperature, relative humidity, pressure, and solar radiation[7]. The observed radar precipitation calibrated with rain gauge was obtained also from AMeDAS. The temporal resolution is 1 hour at 2.5 km. The quantitative precipitation forecast was obtained from the operational JMA's Non-Hydrostatic Model (JMANHM) with 10 km horizontal resolution, issued 4 times a day (till Feb 2006). The data can be accessed at the University of Tokyo's site: http://gpv.tkl.iis.u-tokyo.ac.jp/GPV/.

4. RESULTS AND DISCUSSION

This application attempts to show the flood reduction using the distributed biosphere hydrological model coupled with dam operation forced by forecast rainfall. The highest flood peak between 2002 and 2005 was selected which corresponds to typhoon # 6, 8-12 July 2002. The model parameters were calibrated and validated in previous work[7] for the period 2001 and 2004. Mainly, it was compared the simulated river discharge and Land Surface Temperature (LST) to the observed ones in-situ and from satellite respectively. The WEB-DHM model runs at 1 h time step while the optimization horizon is 18 h according to the lead-time forecast. It was set an initial condition several hours before the event using observed forcing and dam data. Three dams arranged in parallel namely Fujiwara, Aimata and Sonohara were selected to reduce floods at Maebashi gauging station as seen in **Fig. 2**. The model response to the quantitative precipitation forecast (QPF) compared to the observed radar (RAD) is shown in the sequence of **Fig. 3.** It can be noticed from the hyetographs (upper part) and hydrographs (lower part) the shifting of the forecast signal QPF from overestimation to underestimation during the 3 key intervals for flood control. The threshold discharge that hints the system to start was defined as 750 m³/s at Maebashi accordingly[11]. The forecast error, defined as the ratio of forecast to observed rainfall, at drainage areas can be seen in **Fig. 4.** Except for Sonohara dam, they show clearly the shifting from overestimation to underestimation. The suggested dam release by the system against the observed release can be seen at the bottom of **Figs. 5**. It is evident the early release from the three dams according to the QPF. The water level fluctuations are displayed at the upper part of **Figs. 5**. The suggested release becomes constant over 6 h due to the issuing interval of QPF. It was not suggested higher release for Aimata dam (i.e closer to min. level) due to the underestimation of QPF. The flood peak reduction at Maebashi in **Fig. 6** was obtained

using the suggested release using QPF but verified with observed radar (i.e. actual) rainfall.
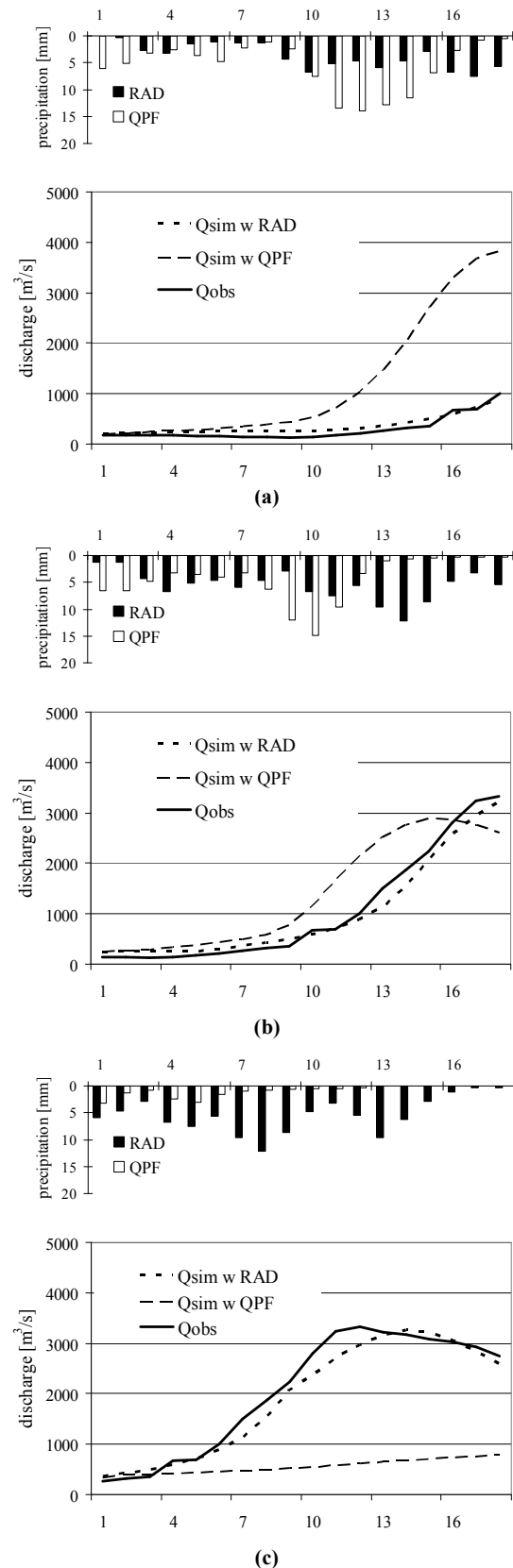
Fig. 3 Simulation sequence at Maebashi station using QPF issued at 00z (a), 06z (b) and 12z (c) on 10 July 2002
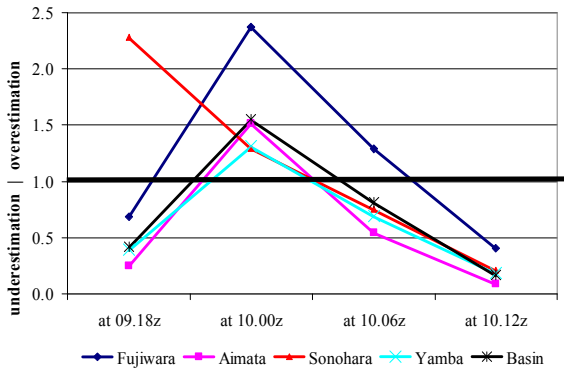
Fig. 4 Area precipitation ratio QPF over RAD, 09-10 July 2002

flood volume at the control point and free volume at reservoirs. Then, a monetary value per water volume could show cost/benefit of water allocation.

The simulation of Yamba dam effect, in **Fig. 7,** shows little increase in water level due to its massive storage capacity of 107 millions m³. The system also encourages storing water at reservoirs for future usage as the simulated water levels are higher. Actually, at the end of the event 2002, the water levels of the dams were higher than their initial levels as seen in upper **Figs. 5**. In this flood event the overestimation of QPF at the first analysis step was beneficial for the system to start releasing water from dams, but this can not be generalized. In case the overestimation of QPF would have persisted during the whole event a higher release volume would have meant loss of water at the end. However, if underestimation of QPF would have dominated the whole event, the risk not to start the system would have been even more critical. From **Fig. 6,** a comparable flood control improvement was reached using the suggested instructions of the system against the activation of Yamba dam. Then, investing on the improvements of integrated dam management and atmospheric meso-scale model output, as the construction of new storage structures seems to be important in the upper Tone River reservoir system.

5. CONCLUSION & OUTLOOK

It can be concluded that the coupled distributed biosphere hydrological model with dam operation and optimization function is able to intake quantitative precipitation forecast patterns. The suggested release instructions showed further flood peak reduction down stream and additional volume storage for water-use which could be used for agriculture or hydropower generation.
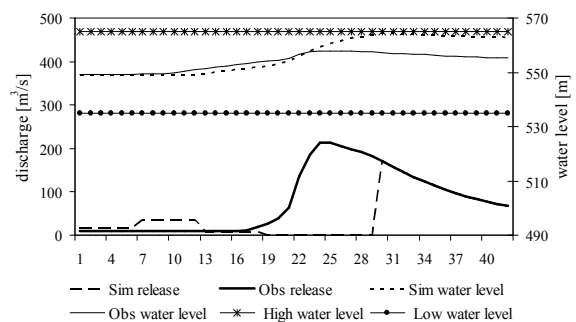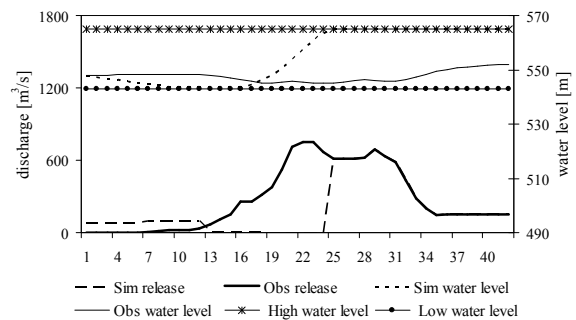
This approach can be useful in humid mountain and highly vegetated basins, like in Japan, Vietnam[9),17)], and Taiwan[10),12)] suffering from typhoons attacks frequently.

The objective function minimizes two terms:
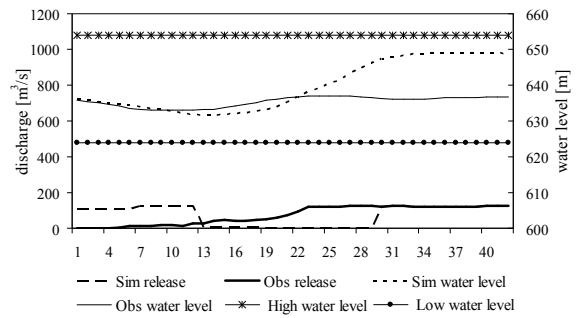
(a)

(b)

(c)

Fig. 5 Simulation of Fujiwara (a), Aimata (b), Sonohara(c)dams using suggested release from 10th(00z) to 11th(18z) July 2002
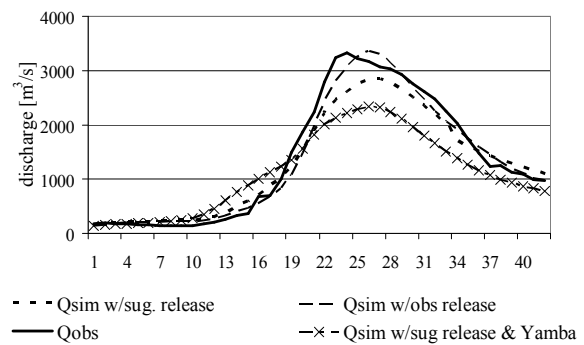

Fig. 6 Flood reduction at Maebashi using suggested release from 10th(00z) to 11th(18z) July 2002
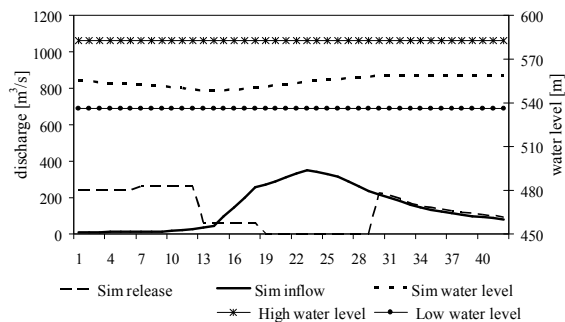
Fig. 7 Simulation of Yamba dam from 10th(00z) to 11th(18z)

The results indicate that direct compensation from the previous performance of the forecast precipitation might not always be correct since shifting from overestimation to underestimation and vice versa was found. Actually, defining a range of the forecast inaccuracy seems to the adequate approach to make sound decisions and contribute to societal benefits reducing flood damages.

After the flood peak, sudden operation is seen in Fig. 5 due to the shift from suggested (by the system) to observed (rule curves). To avoid these large differences, the release could be constrained proportional to the gradient in a step-by-step basis turning to normal operation.

One step processing time in the application is around 5 hours with a 2 GHz processor which can be reduced using a faster unit. The processing time should be kept lower than the issuance interval in real-time operation.

Since the missed/overestimated precipitation pattern might be located in the surroundings of the basin, a weighting of the forecast error could be extended to a wider domain accounting location, intensity and extension. Moreover, the single signal of the quantitative precipitation forecast could be perturbed according to the inaccuracy of the forecast generating ensemble members of rainfall. After forcing the distributed biosphere hydrological model, an ensemble stream flow can be obtained to feed the system and get the dam instructions associated with uncertainty.

Up to this level only quantitative precipitation forecast was used as real-time forcing data; however, it is feasible to include other atmospheric model output data in future developments. Finally, the update of soil moisture condition could interact with Land Data Assimilation Systems (LDAS).

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