APPLICATION OF A DISTRIBUTED HYDROLOGICAL MODEL COUPLED WITH DAM OPERATION FOR FLOOD CONTROL PURPOSES

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A distributed hydrological model was used to simulate hydrological processes in Agatsuma River basin at hourly time steps. By using interpreted radar products and rain gauge rainfall data, simulated inflow to Shimagawa dam have been used as input to a reservoir operation module running simultaneously with the distributed hydrological model. The reservoir operation module uses a storage function approach in order to update the actual volume dam at each time step. Volumes were translated into water levels by using an H-V curve. The operational rule uses the updated water level in order to decide release. The developed scheme offers an easy way to modify the operation rule; therefore, it allows for the incorporation of an optimization scheme in future research. To reduce potential damage of floods and droughts in Tone River basin an optimal reservoir operation scheme will play an important role in the protection of downstream areas and contribute to effective use of water resources.

Key Words: *Tone River, Distributed Hydrological Model, Reservoir Operation, Spatial Rainfall, Flood Forecast*

1. INTRODUCTION

Floods and droughts have been affecting Human beings since ancient times. In recent decades flood events have occurred at higher frequency and magnitude, particularly in humid regions due mainly to a changing climate and human activities.

Recent extreme flood events have been causing enormous disasters; therefore, the need to reduce them is latent and growing. More than ever the ability to efficiently forecast and manage these events plays a key role in protecting human lives and avoiding other material damages.

An extreme event can be substantially reduced by an optimal dam operation scheme assuming that reservoir capacity is sufficient to attenuate floods or store water for dry season. However, one should take into account that complex River systems need more than one operating reservoir, not only used for flood control purposes, but also for irrigation, water supply, power generation and so on.

While reservoirs are operated by a unique and basic operational rule in normal conditions, experience and judgment of reservoir operators are also needed at extreme events. In order to make an appropriate decision, state variables need to be calculated such as inflow to reservoir. A common practice to estimate inflow is to use a lumped model which assumes a uniform rainfall value throughout the basin as an input. Recent studies[1), 2)] have shown that distributed hydrological models when used in combination with spatially distributed radar rainfall and other remote sensing products can better estimate discharges than earlier lumped methods.

Real-time reservoir operators are concerned with the optimal operation of an existing reservoir system as well as decisions regarding releases for various purposes within short time frames[3)].

An efficient approach for solving multi-reservoir systems is to employ a comprehensive hydraulic simulation coupled with an optimization model to solve the overall control problem[4)]. Therefore, a model structure in its simplest form needs to be established and validated as a first step in order to achieve optimal multi-reservoir operation. The main goal of this study is to validate a coupled distributed hydrological model with a reservoir operation module using spatially distributed radar rainfall.

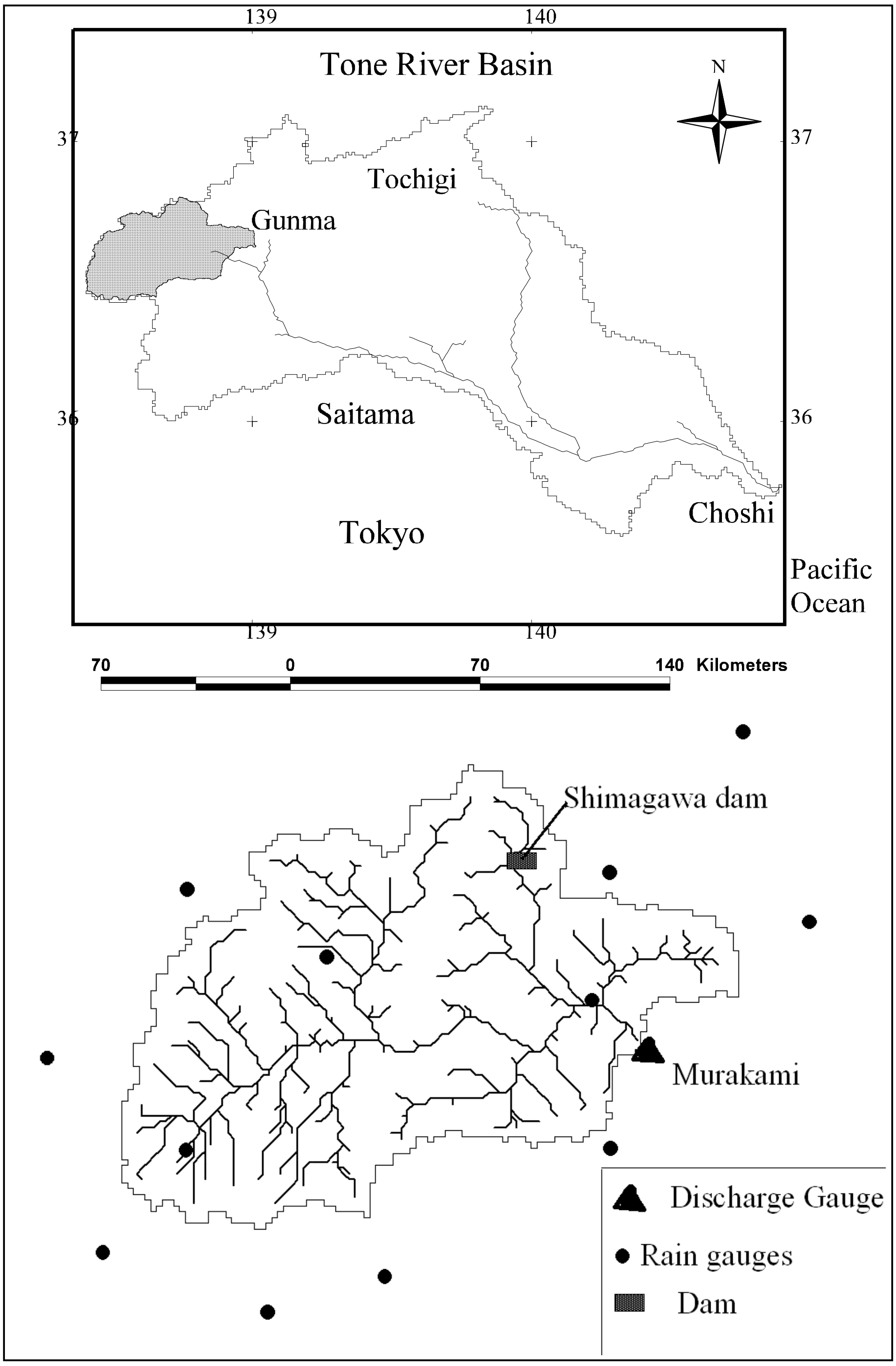

Fig.1 Study area

2. STUDY AREA

The Agatsuma River Basin as seen in upper **Fig.1** located in the northwest upper stream of Tone River Basin, Kanto Region of Japan has been selected as a study area. The Agatsuma River flow contributes to Upper Tone River's discharge. The Tone River is a very important source of water supply, power generation for Tokyo area, and therefore its management is crucial.

The simulated area of 1230 km^2 is delineated upstream of the Murakami discharge gauge as seen at bottom of **Fig. 1**. The Main River channels flow southerly and easterly to Murakami gauging point.

Table 1 Characteristics of Shimagawa dam, Agatsuma basin.

Start/Complete [year]	Drainage [km2]	Height [m]	Storage [Mm3]
1980/1999	31.75	89.5	8.6

Elevation varies from 278 m to 2511 m with an average of 1064 m which reflects the mountainous nature of the region. The mean annual precipitation is approximately 1400 mm with heavy rainfall events during July, August and September, normally are associated with typhoons and frontal line activities.

In the study area, there are small operating dams mainly for hydropower purposes due to rich baseflow which is present throughout the year. This paper targets the Shimagawa dam for the development of a basic dam operation module embedded in a distributed hydrological model. The Shimagawa Dam's characteristics are described in **Table 1**.

The Shimagawa dam is operated by Gunma Prefecture, and is used for power generation and flood control. A uniform minimum outflow throughout a hydrological year needs to be secured in order to support power generation. On the other hand, when heavy rainfalls occur, flood's peaks are attenuated in the reservoir. Finally, in dry season stored water is needed to be released to feed downstream.

3. METHODOLOGY

The data preparation and structure of a coupled model, consisting of a distributed hydrological model and a reservoir operation module, will be described in this chapter.

(1) Distributed Hydrological Model (DHM)

A DHM was used to simulate the spatial distributed hydrological processes in the study area including simulations of the inflow to the reservoir and routing of water in River network system. The employed DHM in this study is a grid-based Geomorphology- Based Hydrological Model[5)] (GBHM) where the computing unit is the geometrically symmetrical hillslope. A hillslope element is viewed as a rectangular inclined plane with a defined length and unit width. Inclination angle is given by surface slope, and also bedrock is assumed parallel to the surface.

Since GBHM is a physically-based hydrological model, it simulates hydrological processes using two models. First, the hillslope model evaluates hydrological processes such as canopy, interception, evapotranspiration, infiltration, surface flow, subsurface flow, as well as exchanges between groundwater and surface water using governing equations. Second, the river network routs water using the kinematic wave approach. In this order simulation is performed at each sub-basin, and linked by the Pfafstetter scheme[6)]. Moreover, every sub-basin is divided in a number of flow intervals considering the flow distance to its outlet. The flow intervals length has been defined as two times the simulation grid size.

Simulation starts when hillslope module calculates surface and subsurface runoff which becomes the lateral inflow to main River channel. The flow routing model then conducts gathered flow from each flow interval from sources to the outlet direction. This procedure dramatically reduces computing time because it is a one-dimensional simulation relying in its geo-morphological properties.

a) Spatial data

The first step to build up the mentioned model was to delineate the modeling area using Geographic Information System (GIS). An aggregated 500 m grid from 50 m grid size DEM was employed as starting point. Once the watershed was delineated, it was divided and subdivided in sub-basins using the Pfafstetter scheme according to its size. In the present model simulation the average sub-basin size is 25 km^2.

Secondly, land use, soil type and Geological maps, were prepared for the study area again using GIS as a tool. A 100 meter digital landuse data available for the region showed 6 categories where forest and grasslands were dominant representing 79.3 % and 9.5 % of the total area respectively. The reminder of the land area represents bare soil, water bodies, built-up area, and sparse grass. Soil type and Geological maps were obtained by digitizing with a tablet from 1:200,000 scale Gunma Prefecture maps which had been prepared for irrigation purposes.

Thematic maps such as surface terrain slope, topsoil depth, and hillslope length, were next derived from data mentioned above. Distribution and depth of topsoil play particularly relevant roles in the simulated discharges values, since subsurface depths and initial saturated zones are defined by topsoil depth. The resulting values for topsoil depth ranged from 1 to 5 m with an average of 2 m. The soil map was obtained by considering geology, slope and landuse. For instance, forested areas with loose material and gentle slope are most likely to have higher topsoil depths than other combinations.

Sub-grid parameterization was carried out using the finer grid size of 100 m and 50 m in order to consider the heterogeneity of landuse and length of hillslope elements respectively in a 500 m grid. In the case of landuse a percentage of cover was applied. Total length of hillslope in a 500 m grid was extracted from small hillslope lengths of 50 m grids. The equivalency was calculated by dividing the area of a grid, which in this case was 0.25 km2, by the total length of streams extracted from 50 m DEM. In this way, a hillslope length becomes smaller at dense stream networks [1].

b) Temporal data

Once the spatial distribution of the area was set-up, time series data were prepared including: rain gauge and interpreted radar products. The Automated Meteorological Data Acquisition System (AMeDAS) stations, which provide hourly rainfall data, are located inside and surrounding the basin as shown in **Fig. 1**. Since rain gauge is point data, it was interpolated by using Thiessen polygons. Moreover, the Ministry of Land Infrastructure and Transportation (MLIT) provides hourly radar rainfall products with accurate calibration at 2.8 km spatial resolution for 2001.

(2) Reservoir operation module

A storage function approach was used to express the change in volume with time as inflow minus outflow (Eq.1).

$$\frac{dV}{dt} = Qin - Qout \qquad (1)$$

Once inflow, initial conditions, reservoir characteristics (e.g. water level and volume curve), and basic operational rules are given, outflow from reservoir can be simulated[7]. Eq.(1) can be expressed by finite difference as:

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

In Eq.(2) index *1* means that the current time step and *2* next time step, and Δt is time interval. Rearranging Eq.(2) reservoir storage at next time step, V_2 can be obtained, as:

$$V_2 = V_1 + \left(\left(\frac{Q^1 in + Q^2 in}{2} \right) - Q^1 out \right) \Delta t \qquad (3)$$

In Eq.(3) $Q^1 out$ represents the assumed constant outflow release for time period between *1* and *2*. The inflow to reservoir is simulated by hydrological model as well as the initial outflow. Current volume V_1 and water level need to be set up as initial conditions. Then, next step volume can be calculated using Eq.(3). Employing the water level and volume curve, the next time step water level can be estimated from V_2 using linear interpolation. Once water level for next time step is evaluated, the release can be calculated using an operational rule. This procedure can be summarized in **Fig 2**.

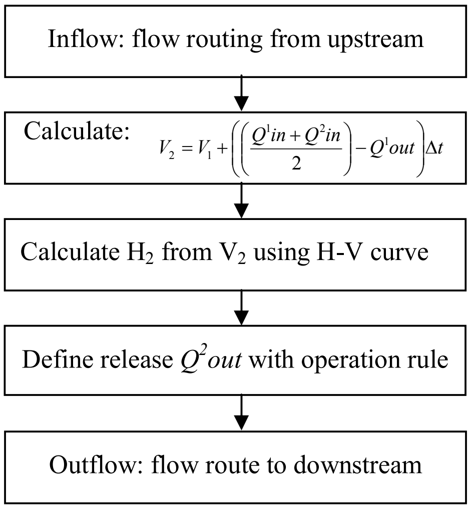

Fig.2 Flowchart of reservoir operation module

In the present model, a simple linear operational rule defines water release *R* according to actual dam operation using updated water level *H*, see Eq.(4).

$$R = a * H - b \qquad (4)$$

The parameters *a* and *b* from Eq.(4) were calibrated by analyzing the relationship of observed releases and water levels of dam operation for summer 2001.

Moreover, reservoir constraints such as minimum and maximum outflow, water level, and storage capacity were considered in order to define the boundary or limits for water release schedules. Taking a look at **Fig.2** after water level H_2 is calculated, the water release can be defined by Eq.(4). The Shimagawa reservoir and the location of the release gates provide natural attenuation of inflow during the flood season in normal conditions.

Once the reservoir operation scheme was defined, the Shimagawa dam site was located in the River network of the DHM by sub-basin code and flow interval number. In this way the coupling of DHM and reservoir operation module was carried out.

4. MODEL APPLICATION

The described procedure has been applied for the month of August 2001 due to flood season and data availability. A one hour time step was used for running the DHM. The initial conditions, including soil moisture and groundwater level, were specified by running model a month prior simulating period.

The hydraulic conductivities of top layer near surface and the groundwater hydraulic conductivity were calibrated by running the GBHM from June to October 2001. The calibrating method was conducted by trial-and-error comparing simulated and observed discharges at two points: the inlet to the reservoir and Murakami gauge. Since hydraulic conductivity varies with soil type, it was necessary to analyze one variable at time and fix others. Repeated manual changes were also carried out due to the high non-linearity of hydrological processes.

5. RESULTS

Simulation results from Agatsuma River basin were examined to the observed discharges in the flood peak event of August 21-24, 2001 due its magnitude within the whole month. Two different types of rainfall data have been used: interpolated rain gauge (point) and spatially distributed radar products. **Fig.3** and **Fig.4** show the results of model performance at inlet to Shimagawa reservoir using both types of inputs. In general, it can be seen that both simulated hydrographs show a good approach to observed ones. However, the hydrograph obtained using radar rainfall product (Sim radar) in **Fig. 4** has a closer representation to observed values (Obs inflow) than rain gauge (Sim rain gauge) in **Fig. 3**. At Murakami discharge gauge which represents the total simulated area, hydrographs using radar rainfall input also show a better approach compared to rain gauge data, see **Fig. 5**.

Moreover, the Root Mean Square Error (RMSE) defined in Eq.(5) has been used to compare performance of both rainfall input types, where *Qsim* and *Qobs* are simulated and observed discharges at each time step and *N* is the total number of time steps.

$$RMSE = \sqrt{\frac{\sum (Qsim - Qobs)^2}{N}} \qquad (5)$$

Since August has 31 days, 744 time steps were considered and calculated errors using rain gauge and radar data were 2.593 and 1.566 respectively.

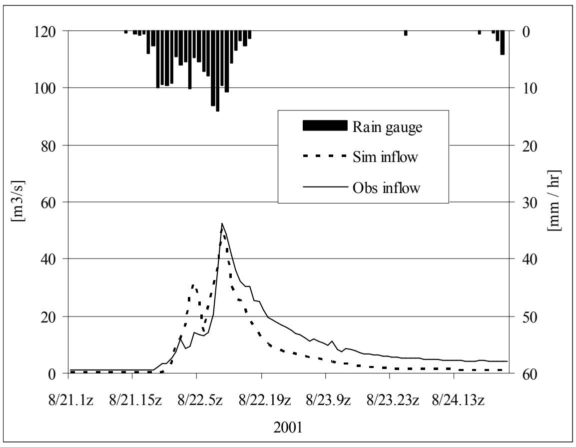

Fig.3 Inflow to Shimagawa dam using rain gauge

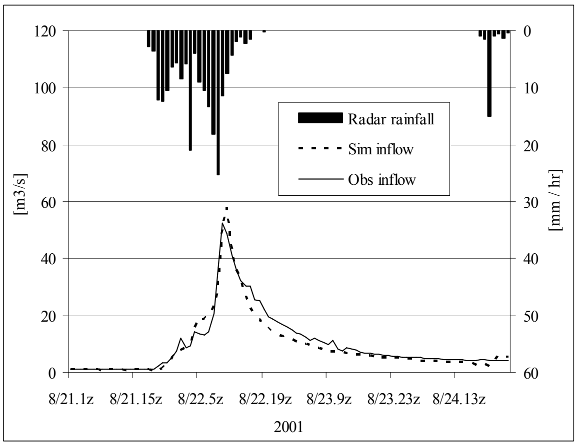

Fig.4 Inflow to Shimagawa dam using radar rainfall

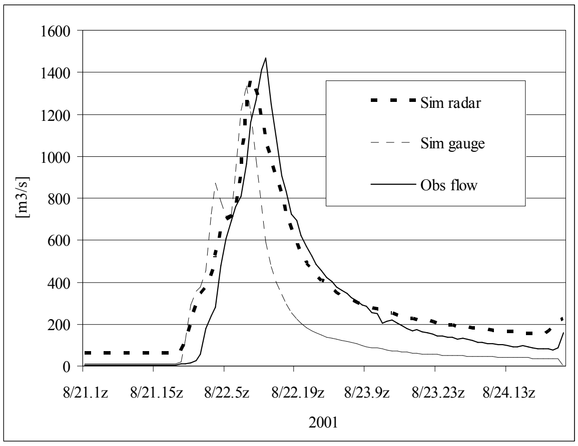

Fig.5 Discharge at Murakami

In order to examine the performance of reservoir operation module, simulated releases (Sim outflow) from the reservoir using radar data were compared to the observed values (Obs outflow) as shown in **Fig. 6**. The RMSE value obtained comparing simulated to observed releases was 0.8 using Eq.(5).

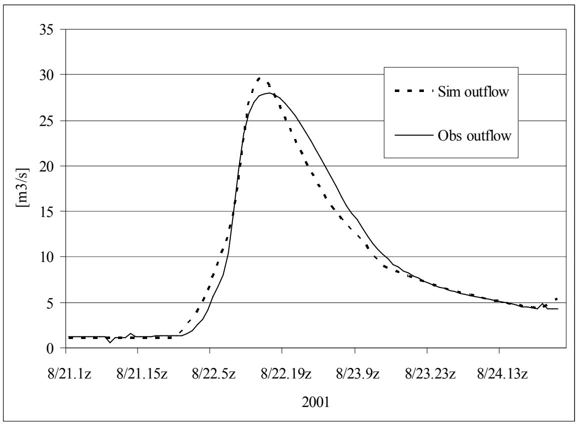

Fig.6 Outflow from Shimagawa dam

Execution time of simulated area of 1230 km^2 using 500 m grid size at hourly time step lasted only 3 minutes in a personal computer Pentium IV 1.3 GHz processor.

6. DISCUSSION

The Agatsuma River basin upstream of Murakami has been simulated using a distributed hydrological model in order to improve prediction of discharge. Simulated and observed hydrographs were compared at Shimagawa dam's inlet and at Murakami gauging point. Simulated hydrographs using spatially distributed radar products as an input demonstrated better performance than rain gauge data to represent flood peak at August the 22nd. The accuracy of simulated flood peaks at Murakami **Fig. 5** are lower compared to ones in **Fig.3** and **Fig.4** because of the difference in drainage area and the lack of observed discharge data for calibration.

The operation of Shimagawa dam was simulated by a reservoir operation module where inflow was provided from calibrated hydrological model. Similarly to hydrological model, reservoir operation module's performance has been proven efficient comparing release water hydrographs in **Fig. 6** and computed RMSE error which was less than one.

A linear operational rule has been developed to define water release only for August 2001 which does not necessary represents a whole hydrologic year since snow melting from winter season has not been included.

Comparing hydrographs in **Fig. 4** and **Fig. 6**, it can be noticed that the flood peak at dam's inlet was attenuated by almost the half in magnitude.

During the simulated flood peak on August the 22nd, the Shimagawa reservoir was at about 20 percent of maximum storage capacity which means that a flood of even higher magnitude could have been attenuated.

Execution time may be reduced to under a minute by using more processors or a higher speed single unit. Low computational cost is the basic and main advantage of the GBHM which may facilitate real-time dam operation in the future.

In summary, a coupled distributed hydrological model with a reservoir operation module using spatially distributed rainfall has been successfully validated showing the following highlights:

-advantage using radar rainfall products
-dam inflow & downstream flood forecast
-simulation of reservoir operation
-low execution time

The spatial and temporal variability of rainfall patterns can be updated or forecasted in order to simulate accurate inflow to the reservoir and downstream conditions. In this way, this coupled model can perform analysis of different scenarios such as storing more volume at reservoir by modifying the operational rule's parameters. Therefore, it might be a useful reference tool for dam operators to improve decisions in flood management.

At present status only one reservoir has been successfully simulated using the coupled model; however, the results of this study show the feasibility to simulate a dam network with multi-purpose use in real time. An appropriate optimization scheme of operational rule might also be coupled with present model in order to improve water resources management.

In future simulations the area will be expanded to combine the Agatsuma basin with the Okutone basin and its 5 operating reservoirs.

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