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Vorgeschlagene Zitierweise/Suggested citation:
Koike, Toshio; Kuria, David N.; Wang, Lei; Valeriano, Oliver Cristian Saavedra (2008): A Flash Flood Control System Based on the Global Earth Observation System of Systems. In: Wang, Sam S. Y. (Hg.): ICHE 2008. Proceedings of the 8th International Conference on Hydro-Science and Engineering, September 9-12, 2008, Nagoya, Japan. Nagoya: Nagoya Hydraulic Research Institute for River Basin Management.

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A FLASH FLOOD CONTROL SYSTEM BASED ON THE GLOBAL EARTH OBSERVATION SYSTEM OF SYSTEMS

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ABSTRACT

Water-related hazards usually occur as causes and consequences of large water cycle fluctuations on global and regional scales, while disasters and damages due to these hazards happen through strong linkage with human activities on a local scale. The observations and predictions of water-related hazards and their damages can be enhanced by combining global Earth observation and prediction systems and local information. In this context, downscaling of the water cycle from global to regional and local scales is a key integration function. General circulation models currently used for predicting weather and climate have coarse spatial resolution and thus cannot capture the details of topography and land use nor resolve important cyclonic disturbances or similar-sized circulation features. This precludes an accurate representation of precipitation on the scales of individual grid boxes. The method to obtain regional-to-local scale information from larger-scale general circulation model data is referred to as downscaling. The flash flood control system of the Global Earth Observation System of Systems takes maximum advantage of global Earth observations and predictions and develops a downscaling system coupled with satellite-based data assimilations and distributed hydrological models to disseminate usable information on a river basin or smaller scale for decision making in disaster mitigation and water resource planning.

Keywords: flood, water cycle, Global Earth Observation System of Systems, general circulation model, remote sensing, distributed hydrological model

1. INTRODUCTION

Large fluctuations of regional and local water cycles intensify flood hazards, which lead to large socio-economic losses. Owing to the effects of atmospheric and ocean circulations and the variations in water storage as snow and soil moisture, local and regional water cycle fluctuations are correlated for different areas and seasons. Even when a more localized water-related event, a flash flood, is addressed, we need to consider its connections with other areas or regions under the global water cycle variation.

There is growing concern about the effect of global warming on flood risks and the need to address them in a more coordinated way. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) summarized and projected the trends of precipitation in the past and future. To quote from the report, "The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapor" and "It is very likely that heavy precipitation events will continue to become more frequent." (IPCC, 2007). Flood hazards will intensify owing to global warming. We need timely, quality, long-term, global water cycle information as a basis for sound and effective flood risk management.

The Third Earth Observation Summit in Brussels, February 2005, established the Group on Earth Observation (GEO) and endorsed the 10 Year Implementation Plan for the Global Earth Observation System of Systems (GEOSS). The goal of GEOSS is to achieve comprehensive, coordinated, and sustained observations of the Earth system to improve monitoring of the changing state of the planet, increase understanding of complex Earth processes, and enhance the prediction of the impacts of environmental change. GEOSS will meet the need for all nations to benefit from access to timely, quantitative, and high-quality long-term global data and information as a basis for sound decision-making. "Improving water resource management through better understanding of the water cycle" is one of the nine socio-benefit areas targeted by GEOSS (GEO, 2005).

By making maximum use of the opportunities for global observations, predictions and data integration provided by GEOSS, this paper develops a downscaling system that converts the global earth observation data and prediction outputs to usable information for sound decision-making on flood control on a river basin or smaller scale.

2. SYSTEM CONFIGURATION

General circulation models (GCMs) currently used for predicting weather and climate have a grid-box resolution that cannot capture the details of orography nor resolve important cyclonic disturbances or similarly-sized circulation features. This precludes accurate representations of precipitation on scales of individual grid boxes and flood discharge on a river basin scale. The method for producing local-to-regional scale information from larger-scale GCM data is called downscaling.

GEOSS provides global observation and prediction data and their integration functions, which improve dynamical downscaling by effectively combining GCM outputs, satellite observation data, and *in situ* observation data and socio-economic needs on a river basin or smaller scale. The GEOSS flash flood control system (GEOSS/FFCS) consists of three components: a satellite-based atmosphere–land coupled data assimilation system (SALDAS), a water and energy budget-based distributed hydrological model (WEB-DHM), and decision-making support tools for flood control including dam operation and evacuation instructions. GEOSS/FFCS is now being developed for the GEOSS data integration and analysis system (DIAS).

3. SATELLITE-BASED ATMOSPHERE–LAND COUPLED DATA ASSIMILATION SYSTEM (SALDAS)

While GCMs are best at simulating evolving and future changes in climate systems, they are unable to produce mesoscale and local atmospheric phenomena. Thus downscaling methods are necessary to bridge the gap between global scales and smaller modeling scales. In this paper we use a high spatial resolution mesoscale model and nest it within a GCM. This nesting is realized using initial and boundary conditions from the GCM output. This approach alone is not adequate for reproducing local phenomena and extreme events because nesting does not include accurate land surface initial and boundary conditions, and thus the approach misses important physical processes such as convection and local circulation (Boussetta et al., 2007).

To physically address the mechanisms of atmosphere–land interactions based on land surface conditions, the land data assimilation system (LDAS) developed by Boussetta *et al.*, 2007 is used to augment the stand-alone regional atmospheric model. While this system addresses land surface heterogeneities, it does not address atmospheric components in a direct way. This system assimilates lower frequency microwave brightness temperatures to improve estimation of land surface conditions.

It has been argued that the structure of the atmosphere is strongly dependent on cloud microphysics because microphysical processes are responsible for the release of latent heat, formation of precipitation and precipitation evolution outside of clouds (Grabowski, 2000). Clouds and general circulation of Earth’s atmosphere are linked in an intimate feedback loop, where clouds result from water vapor transport and cooling by atmospheric motion, but the forcing for atmospheric circulation is significantly modified by vertical and horizontal gradients in radiative and latent heat fluxes induced by the clouds (Wang et al., 2000). Changes in cloud vertical structure (locations of the cloud top and base and the number and thickness of layers) affect the atmospheric circulations at local to global scales by modifying the distribution of radiative latent heating rates within the atmosphere.

Mirza et al. (2007) developed a satellite-based cloud microphysics data assimilation system (CMDAS) for assimilating brightness temperature at high microwave frequency to improve estimation of cloud properties over ocean and sea surfaces. The general framework of CMDAS, shown in Figure 1, includes the Lin ice cloud microphysics scheme as a model operator, a four-stream fast microwave radiative transfer model in the atmosphere as an observation operator, and a global minimization method that is known as the shuffled complex evolution. CMDAS assimilates the satellite microwave radiometer dataset of the advanced microwave scanning radiometer for the Earth observing system (AMSR-E) and retrieves integrated water vapor and integrated cloud liquid water content. CMDAS improves the performance of the cloud microphysics scheme by introducing mesoscale heterogeneity into the external global reanalysis data, which improves the accuracy of the initial atmospheric conditions.

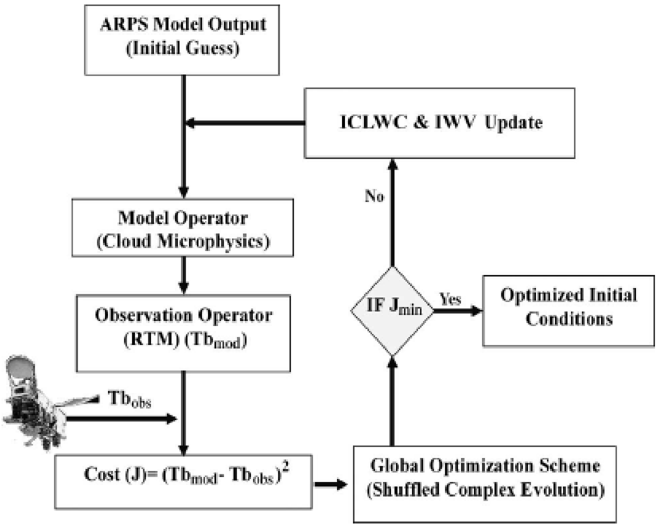

Figure 1 CMDAS framework (Mirza et al., 2008).

GEOSS/FFCS SALDAS combines LDAS and CMDAS, as shown in Figure 2, by refining and coupling them with a physically based land–atmosphere coupled radiative transfer model (LA-RTM) that can represent microwave radiative transfer in soil by considering surface roughness effects, volume scattering and emission in the soil volume, and

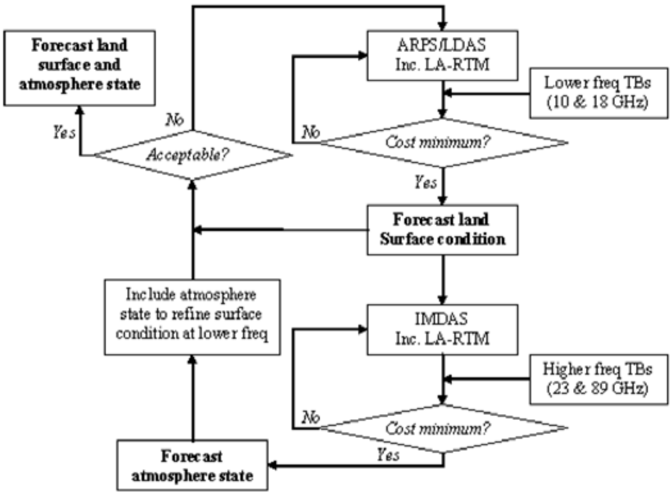

Figure 2 SALDAS framework.

atmospheric emission and scattering. Both data assimilation schemes use the advanced regional prediction system (ARPS), developed at the Center for Analysis and Prediction of Storms at the University of Oklahoma (Xue et al., 2000, 2001, 2003), and the system is coupled with simple biosphere model 2 (SiB2) developed by Sellers et al. (1996). To account for precipitation estimation, SALDAS includes modifications allowing direct estimation of snow and rain rates as additional assimilation variables.

Step 1:

LDAS, with LA-RTM as the observation operator, assimilates the brightness temperature observed by AMSR-E at its lower frequencies (6.9, 10.7 and 18.7 GHz). Cloud water, ice and light precipitation can be assumed transparent to lower microwave frequencies, and thus the retrieved land surface conditions are representative of prevailing surface conditions.

Step 2:

Output from LDAS is used to provide initial and boundary conditions for CMDAS. LA-RTM embedded in CMDAS uses microwave emissivities converted from the lower frequencies to higher frequencies (23.8 and 89.0 GHz) as the boundary condition of LA-RTM in the atmosphere. Then CMDAS retrieves water vapor, cloud water, cloud ice, rain and snow columns describing the atmospheric state coupled with the ARPS Lin ice microphysics scheme.

Step 3:

This retrieved atmospheric condition is fed back to the LDAS step to refine the surface condition. SALDAS can then provide a reliable land surface and atmospheric state that can improve the accuracy of rainfall prediction.

SALDAS was applied to the National Centers for Environmental Prediction (NCEP) global forecast system (GFS) reanalysis data and AMSR-E data archived in GEOSS/DIAS at the University of Tokyo, for downscaling to a mesoscale area of the Tibetan Plateau. Figure 3 shows the assimilated integrated cloud liquid water and rain. Using the assimilated atmosphere products as an initial condition of ARPS, the 24 hour rainfall was predicted. Figure 4 shows the predicted rainfall distribution in comparison with the satellite infrared image at the same time and the prediction result without the use of SALDAS and only using ARPS nesting and prediction. The result of the SALDAS validation for the Tibetan Plateau shows better consistency with the satellite infrared observation.

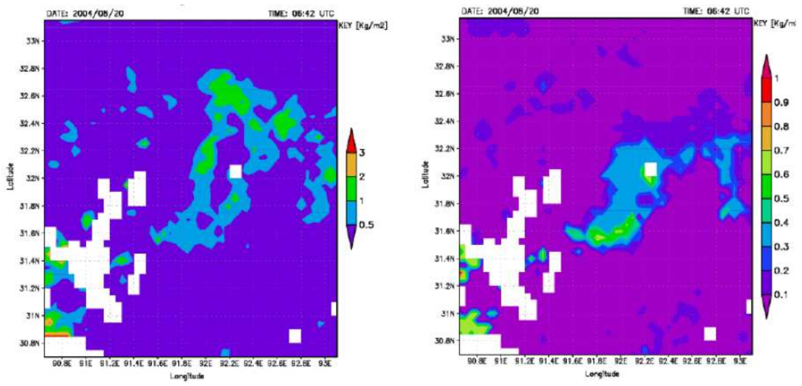

Figure 3 Integrated cloud liquid water (left) and rain water (right) retrieved by SALDAS.

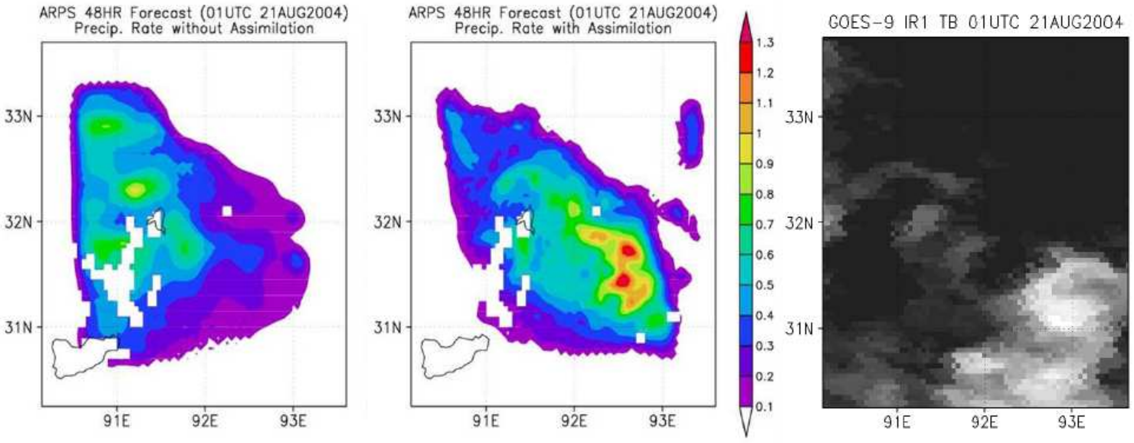

Figure 4 24 hour rainfall predictions by ARPS with only nesting from the GCM (left) and using an initial condition derived from SALDAS (centre), and a satellite infrared image.

4. WEB-DHM

To meet the increasing societal needs for improving flood prediction, including predictions of climate change impacts on the global to local water cycle variations, there has been a great research effort to apply hydrological models throughout the world to better understand water and energy cycle variations. Much of this work has involved coupling distributed hydrological models (DHMs) with land surface models (LSMs), since this coupling potentially improves the land surface representation, benefiting both the streamflow prediction capabilities of the hydrological models as well as providing improved estimates of water and energy fluxes into the atmosphere (Pietroniro and Soulis, 2003).

DHMs give a distributed representation of the spatial variation and physical descriptions of hydrological processes. In the last two decades, a number of DHMs incorporating new techniques appeared, such as “Systeme Hydrologique Europeen” (SHE) (Abbott et al. 1986; Bathurst et al., 1995) and the geomorphology-based hydrological model (GBHM) (Yang et al., 2004). Though there is improvement over the lumped hydrological models with the representation of spatial heterogeneity, DHMs are still unable to correctly simulate water exchanges at the soil–atmosphere interface and the time evolution of surface soil moisture owing to the conceptual prescription of the land surface and empirical evaporation calculation. This drawback often leads to poor simulation of water flows, particularly floods, after periods of low flows because of the incorrect estimation of the surface soil water content.

LSMs are usually used to provide lower boundary conditions for atmospheric modes. However, owing to the one-dimensionality of current LSMs, most have only considered the vertical water moisture transport, while disregarding the lateral water redistribution due to uneven topography (e.g., Sellers et al., 1996). However, the spatial distribution of land surface wetness has been recognized as one of the most important factors determining land surface heterogeneity, which can significantly affect the energy and water fluxes simulated in atmospheric models (e.g., Fast and McCorcle, 1991; Li and Avissar, 1994; Chen and Avissar, 1994; Avissar et al., 2004). Many studies showed that accurately estimating soil moisture and its spatial distribution is critical for atmospheric model forecasts (e.g., Leese et al., 2001; Pielke, 2001; Findell and Eltahir, 2003).

In this regard, coupling LSMs with DHMs can achieve a lateral water redistribution for LSMs that considers topographical effects, provide better estimates of water and energy fluxes into the atmosphere, and thus improve flood predictions after periods of low water flows, while most DHMs usually have poor accuracy owing to poor representation of the initial soil moisture condition of a flood event.

GEOSS/FFCS includes a WEB-DHM, which couples a realistic LSM, the widely used SiB2, with a GBHM. The overall model structure is shown in Figure 5 and is described as follows.

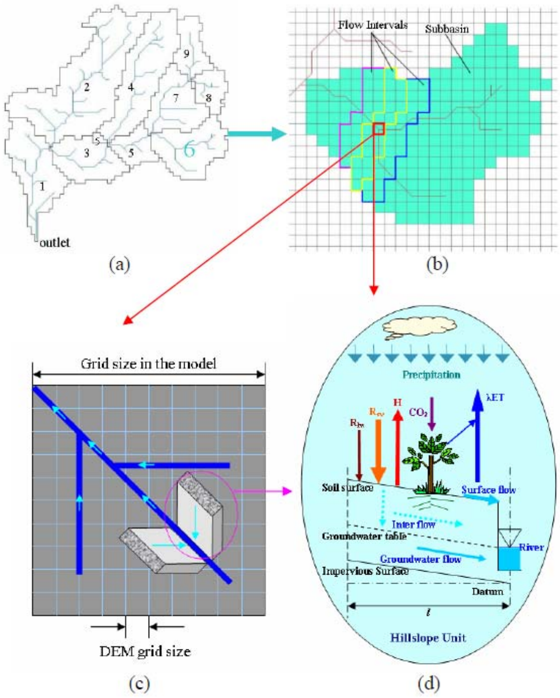

Figure 5 Overall structure as conceptualized in a grid-based WEB-DHM: (a) division from a basin to sub-basins, (b) subdivision from a sub-basin to flow intervals comprising several WEB-DHM grids, (c) discretization from a WEB-DHM grid to a number of geometrically symmetrical hill slopes, and (d) process descriptions of the water moisture transfer from the atmosphere to river.

(1) A digital elevation model (DEM) is used to define the target area and then the target basin is divided into subbasins according to the DEM resolution and needs of the model simulation (see Figure 5a).

(2) Within a given subbasin, a number of flow intervals are specified to represent time lag and

accumulating processes in the river network according to the distance to the outlet of the subbasin. Each flow interval includes several WEB-DHM grids (see Figure 6b).

(3) For each WEB-DHM grid with one combination of land use type and soil type, the improved SiB2 is used to calculate turbulent fluxes between the atmosphere and land surface (see Figures 5b and 5d). The vertical distributions of water for all the WEB-DHM grids in the target basin, such as ground interception store and soil moisture in soil profile, can be obtained in this biophysical process.

(4) Each WEB-DHM grid is subdivided into a number of geometrically symmetrical hill slopes (see Figure 5c), which are the basic hydrological units (BHUs) of the WEB-DHM. For each BHU, the hydrological submodel is used to simulate lateral water redistributions and calculate runoff (see Figures 5c and 5d). The runoff of a WEB-DHM grid is the total response of all BHUs within.

(5) The length of a flow interval is usually assigned as 1.5 or 2 times the width of the WEB-DHM grid. It is practically difficult to identify and represent all the river channels in a grid-based DHM. For simplicity, the streams located in one flow interval are lumped into a single virtual channel. All the flow intervals are linked by the river network generated from the DEM. All the runoff from the WEB-DHM grids in the given flow interval is accumulated into the virtual channel and led to the outlet of the river basin.

The results of application of a WEB-DHM to the upper Tone river basin of Japan (Figure 6) are shown in Figures 7 and 8. In producing the model, we used a digital elevation model, land use/cover, and soil-type datasets archived in GEOSS/DIAS at the University of Tokyo. The WEB-DHM shows good performance in simulating floods, including those after periods of low water flow. This means the WEB-DHM can provide reasonable initial conditions, especially for soil moisture, by itself for flood prediction after long-term low water flows.

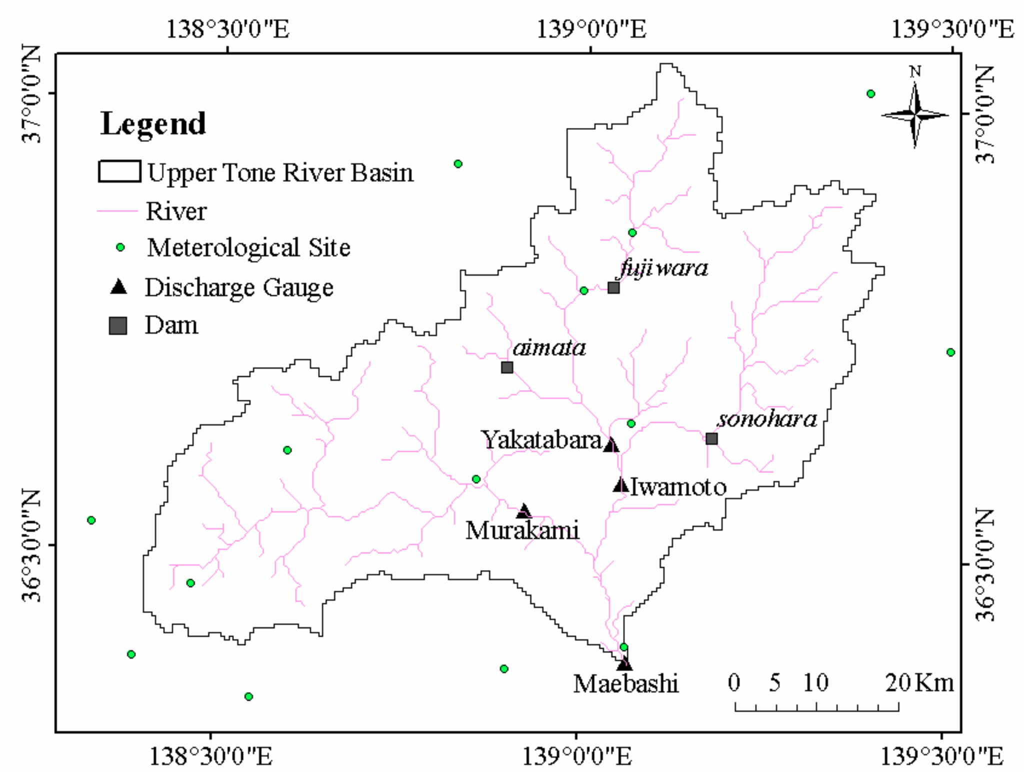

Figure 6 Upper Tone river basin of Japan.

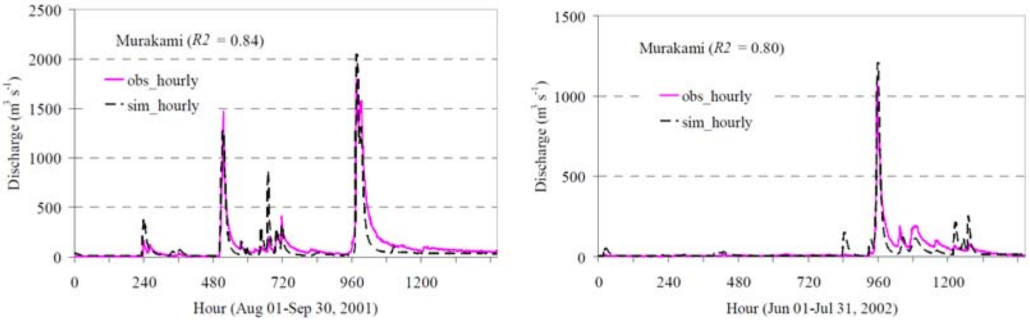

Figure 7 Hourly hydrographs at discharge gauges of Murakami in the flood season of 2001 (left) and 2002 (right), where R2 is the Nash–Sutcliffe model efficiency coefficient.

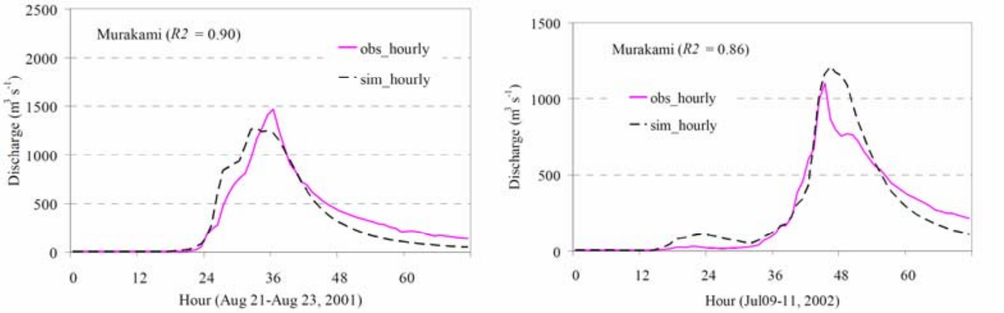

Figure 8 Flood peaks simulated by WEB-DHM on 22 August 2001 (left), and 10 July 2002 (right) at discharge gauges of Murakami, where R2 is the Nash–Sutcliffe model efficiency coefficient.

5. DECISION SUPPORT TOOLS

Real-time flood control operations have been investigated using conceptual, stochastic or deterministic models, often coupled with river channel routing. The control problem is solved by linear, dynamic, and nonlinear programming and simulation approaches. Most approaches used observed data rather than rainfall predictions. There is a growing need for decision support tools that can effectively introduce flood prediction with improved accuracy to aid decision-making in flood control. To meet these needs, GEOSS/FFCS develops an optimization scheme focusing on effective flood control operation of a multi-purpose and multi-reservoir system. The scheme includes

(1) introduction of a quantitative rainfall prediction with an estimated prediction error to an optimization scheme;
(2) introduction of a physically based DHM to address a multi-reservoir system by making maximum use of a spatially-distributed rainfall prediction; and
(3) introduction of multi-purpose optimization functions for obtaining a quantitative solution.

To reduce flooding downstream and store water in dam reservoirs for future use, a desirable discharge Q_{opt_gauge} is introduced as a constant value taking as reference the average discharge during a flood period. Firstly, the WEB-DHM 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 levels of reservoirs are at minimum levels. The potential flood volume $flood\_vol_{dam}$ to be reduced is then quantified as the integrated volume between the simulated discharges

$Q_{without\_dam}$ and Q_{with_dam} in excess of the desirable discharge $Q_{desirable}$ as shown in Figure 9. The total flood volume to be reduced is then obtained by considering all dams. The intersection of $Q_{without\_dam}$ with the desirable flow $Q_{desirable}$ downstream defines stages I and II and is denoted by time *t*. In this way, the system is expected to release an amount less than or equal to the total predicted inflow to dams during stage I to leave enough flood control volume. Once stage II is reached, the gates are closed with the expectation to store water for replenishment. The end of the latter stage is defined by time step τ, which could match the lead-time or extend until the simulated discharge is lower than Q_{opt_gauge}. Therefore, the objective function is defined as that minimizing the absolute difference between the flood volume and the total volume released from dams using a heuristic optimization algorithm, the shuffled complex evolution (SCE), developed by Duan et al. (1992).

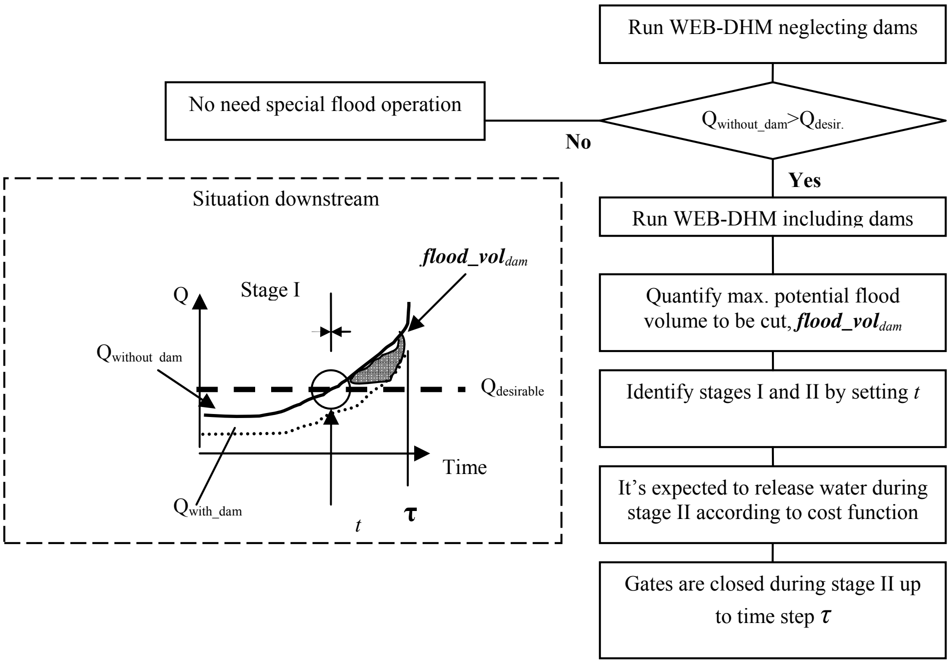

Figure 9 Objective function for flood control and water use.

The mesoscale weather prediction model coupled with the GCM provides meteorological variables, namely grid point values (GPVs), at 0.125 degree spatial resolution issued every 6 hours and records up to 18 hours lead time. GPV data covering all of Japan were originally provided by the Japan Meteorological Agency and are archived from 1 July 2002 to the present day in GEOSS/DIAS at the University of Tokyo. A weight, which is inversely proportional to the standard deviation of the error forecast, is introduced into the objective function. The error is calculated as the simple bias, absolute bias, and root mean square error. In this way, it is expected that lower values of standard deviation (better accuracy of forecast) affect more positively the iteration process of the optimization.

The developed system was applied to an actual dam network on the upper Tone river in Japan. Not only were the flood peak and volume reduced downstream, but also the water volume in the dams was replenished after the flood event. After the iteration process using the SCE algorithm was complete, the optimized water release values for Sonohara and Fujiwara dams were obtained. The dam effect at the Iwamoto gauge determined using the GPV 7–12 rainfall forecast series can be seen in Figure 10 (left). The flood peak and recession curve decreased owing to effective storage of water in the dam reservoirs. The Fujiwara and Sonohara dam status are shown in Figures 10 (center) and 10 (right). Sonohara dam started operating as free-flow

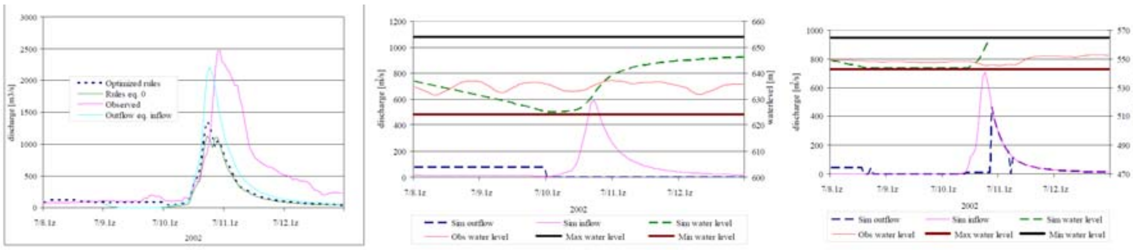

Figure 10 Optimized dam operation using the GPV 7–12 series rainfall prediction at Iwamoto gauge (left), Fujiwara dam (centre), and Sonohara dam (right).

from 10 pm on 10 July 2002, when the maximum safety capacity was reached. On the other hand, the simulated water level for Fujiwara dam was as high as 646.24 m.

6. GEOSS/DIAS

By coordinating the development of Earth observation systems, GEOSS enables better decision making and actions for the benefit of society. It is expected there will be a large increase in the volume and diversity of Earth observations from inhomogeneous data sources during the next decade. GEOSS/DIAS is developing a core system for data integration and analysis that includes the supporting functions of life cycle data management, data search, information exploration, scientific analysis, and partial data downloading. For improving data interoperability, GEOSS/DIAS is developing a system for identifying the relationship between data using the ontology of technical terms and geography. To promote integrated water resource management, GEOSS/DIAS integrates data from Earth observation satellites and *in situ* networks with other types of data, including numerical weather prediction model outputs, geographical information, and socio-economic data.

ACKNOWLEDGMENTS

This research was implemented as a part of the Data Integration and Analysis System project founded by the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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