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Implementation of Real-Time Flood Prediction and its Application to Dam Operations by Data Integration Analysis System

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Despite recent advances in hydrological models and observation technology, the prediction of floods using advanced models and data has not yet been fully implemented for practical use. The major issues in prediction originate from the underlying uncertainty of the initial conditions of the basin and the accuracy of the precipitation forecast. Effective transmission of flood information to corresponding authorities is also necessary when considering countermeasures against an oncoming flood. We present in this article a data archive and model integrated system to overcome these issues. The system realizes flood forecasting by employing a land surface model coupled with hydrological model and an ensemble precipitation forecast model to address the accuracy of initial conditions and precipitation. While the Water and Energy Budget Based Distributed Hydrological Model (WEB-DHM) rigorously estimates the physical state of the basin, the ensemble precipitation forecast model analyzes historical errors in forecasts and returns precipitation ensembles reflecting the uncertainty in the forecast specifically regarding the target basin. A combination of these models yields an ensemble of streamflow forecasts. We further develop a virtual reservoir simulator to enhance the proactive use of forecast information to support decision-making by reservoir managers. These models are integrated into the Data Integration Analysis System (DIAS). The feasibility of the system for practical use is tested against data from recent typhoon events.

Keywords: data-archive and model integrated system, flood forecast, ensemble streamflow prediction, virtual reservoir simulator

1. Intruduction

Flood disasters associated with typhoons and the Baiu front remain serious issues, despite the advancement of observation products and quantitative precipitation forecasts (QPF). Numerous studies have been conducted to address the prevention of such disasters by applying QPF for flood prediction [1, 2]. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has developed radar-derived rainfall data; C-band radar rainfall data, which covers all of Japan; and X-band multiparameter radar rainfall data, which is locally focused but high in spatiotemporal resolution (250 m with 1-min intervals). The Japan Meteorological Agency has developed the Grid Point Value (GPV) database, having 39 h of lead time with 5-km horizontal grid spacing. In principle, this resolution can capture mesoscale atmospheric disturbances. Such scientific resources are among the most advanced available tools. Challenges in predicting river flooding on a real-time basis can be attributed to difficulties in estimating the initial hydrologic state of the basin, such as soil moisture and groundwater storage, and accuracy in the precipitation forecast [3]. Nearly all hydrological models must overcome the issue of initial conditions.

The storage function model, for example, is one of the most common and popular hydrological models practically applied in Japan. With the model's succinct calculation scheme, only a few empirical parameters are required. While the model is known to accurately simulate past flooding events, applying it to real-time forecasts is not straightforward, as the model involves post-event evaluations. For instance, saturated rainfall is considered to reflect the basin's physical state of dryness or wetness, but it is not trivial to estimate such a condition and parameterize the state without calibration, as the physical states of basins vary according to preceding weather conditions.

Uncertainty in initial conditions can be moderated by assimilating observed information into the model by filtering techniques. Sayama et al. [4] introduced the Kalman filter to a distributed hydrological model to address bias errors originating from runoff estimates while assimilating river discharges. Tachikawa et al. [5] applied the particle filter technique to predict water levels by sequentially updating the model parameters, which improved model prediction.

The application of QPF in addition to observed precipitation can extend the lead time of a forecast. However, attention should be paid to QPF accuracy, as this is crucial in modeling discharges. QPF has improved in accuracy over recent decades, along with the development of physical schemes, e.g., microphysics parameterization for improved convective initialization, and advanced data assimilation methods, e.g., three- or four-dimensional variational data assimilation, or the application of Doppler radar data [6]. However, improvement of QPF, particularly for heavy rainfall, remains an issue [7]. With the knowledge that precipitation outputs from state-of-the-art atmospheric models may include quantitative limitations, hydrologists must try applying outputs with best practices to extend the forecast lead time.

In addition to these issues, hydrologists and forecasters may have to consider how their simulation results are utilized when countermeasures against floods are planned. In the case of Japan, evacuation advisories or orders for residents are disseminated by local municipalities, who make such decisions according to advice from river managers. Hence, it is highly important that forecast results are provided to support the corresponding managers to enable confident decisions.

Under these circumstances, the realization of real-time flood forecasts requires hydrological models that can accurately estimate the initial states of river basins and continuously simulate changes of in state from pre- to peri-flooding without relying on data from post-event evaluations. In order to extend the forecast lead time, QPF should be applied, which then implies that the uncertainty in QPF must be evaluated so that QPF-based information can remain valuable in supporting reservoir managers' decisions. The present study develops a flood forecast system that simulates river discharge on a real-time basis, addressing the above issues and challenges. The system is applied to the Upper Tone river basin and its feasibility for practical implementation is examined by evaluating the system's forecast performance through recent flood events in the river basin.

2. Study Site and Flood Events

The Tone River, as shown in **Fig. 1**, is one of the most important rivers in Japan. The river supplies agricultural and industrial water to and around the Greater Tokyo Area, and three-quarters of the Tokyo metropolis's drinking water comes from the Tone River. The river is also important in terms of flood control. When Typhoon Kathleen struck the Kanto region in September 1947, the cumulative rainfall reached 318 mm within three days in the Upper Tone river basin; this caused severe damage in the Greater Tokyo Area. According to the basic policy for the improvement of the Tone River, one-third of the designed flood discharge should be controlled at Yattajima, located at the outlet of the Upper Tone river basin. Therefore, the prediction of river flooding is of significant importance.

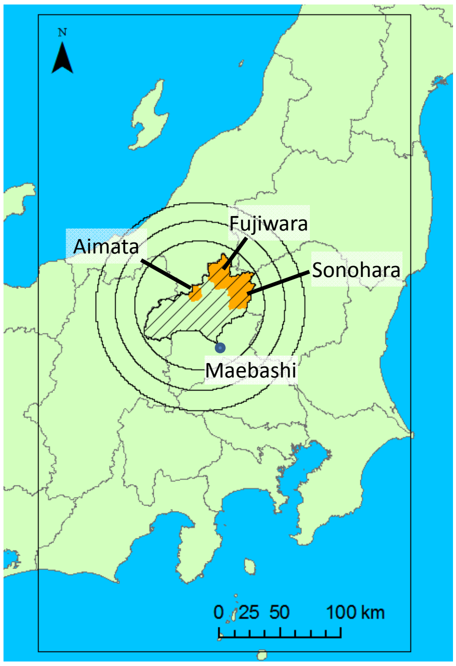

Fig. 1. Upper Tone region with error evaluation zones: Aimata-, Fujiwara-, Sonohara-dam basins, Maebashi basin, three buffer regions, and entire domain.

In this study, the performance of the forecast system is evaluated against three typhoons, all of which made landfall on Honshu Island in Japan and caused severe damage: a) Typhoon Talas (No. 12 in Japanese notation) of September 3, 2011; b) Typhoon Roke (No. 15) of September 21, 2011; and c) Typhoon Man-Yi of September 16, 2013.

3. Methodology

In order to address the objectives of this study, an integrated flood forecast system is developed that connects and controls the following four model components: 1) real-time hydrological model, 2) ensemble precipitation forecast model, 3) ensemble streamflow prediction (ESP) model, and 4) virtual reservoir simulator model. The system is designed to integrate a data archive as well, allowing the handling of models and data without human intervention. The system then realizes hydrological simulation on a real-time basis.

3.1. Real-Time Hydrological Model

As described earlier, the basin's initial state of dryness or wetness affects river discharges during flood events.

Table 1. Relative errors of QPF against observation (upper two rows) and corresponding perturbation weight over different domain.

	Larger forecast error ←							→ Smaller forecast error
Underestimation	0-0.01	0.01-0.05	0.05-0.075	0.075-0.1	0.1-0.3	0.3-0.5	0.5-0.7	0.7-0.9	0.9-1.1
Overestimation	>10	10-5.0	5.0-2.5	2.5-1.9	1.9-1.7	1.7-1.5	1.5-1.3	1.3-1.1	1.1-0.9
Dam sub-basin	3.00	2.50	2.00	1.50	1.00	0.75	0.50	0.25	0.00
Basin	3.50	3.00	2.50	2.00	1.50	1.25	1.00	0.75	0.50
Buffer 1	4.00	3.50	3.00	2.50	2.00	1.75	1.50	1.25	1.00
Buffer 2	4.25	3.75	3.25	2.75	2.25	2.00	1.75	1.50	1.25
Buffer 3	4.50	4.00	3.50	3.00	2.50	2.25	2.00	1.75	1.50
Entire domain	5.00	4.50	4.00	3.50	3.00	2.75	2.5	2.25	2.00

Hence, it is imperative that the initial conditions of the basin, such as soil moisture, groundwater storage, and river flow, are accurately estimated before the onset of flood. In this study, we apply the Water and Energy Budget Based Distributed Hydrological Model (WEB-DHM) [8] to estimate the initial conditions. WEB-DHM couples a distributed hydrological model (GBHM) [9] and the Simple Biosphere Model 2 (SiB2) [10]. In the model, the SiB2 component solves the physical processes of water, energy, and carbon fluxes at the land/atmosphere interface, returning soil moisture content and groundwater storage for each grid of the model domain. The lateral movement of water, surface runoff, subsurface flow, and groundwater flow are simulated within a symmetrical hill slope and then routed to the outlet of the sub-basin. By introducing the so-called flow interval band, which represents the areas having equal time to reach a stream outlet, the model can aggregate runoff processes on the same hillslope, and thereby computational time is greatly reduced.

With the physical scheme used in WEB-DHM, the model has proven its accuracy in estimating soil moisture content, carbon flux, and resulting river discharges [11]. In this study we take advantage of the models' high-speed calculation and accuracy in basin state estimation. The changing basin state is continuously simulated on a real-time basis; the state is used as the initial condition for the ESP model (see below). A detailed model description and the parameters applied in this model are provided by Wang et al. [11]. The only difference from the model in the literature is the use of C-band radar rainfall product as forcing. The original spatial and temporal resolutions of the data are 1 km and 10 min. These are re-gridded to 500-m resolution without interpolation and aggregated into 1-h accumulated rainfall so that the variable would match with other meteorological forcing.

3.2. Ensemble Precipitation Forecast Model

As described earlier, the prediction of rainfall involves uncertainty. Therefore, we take a probabilistic approach and apply the ensemble precipitation method for deriving the ensemble spread [12]. We apply the model developed by Saavedra et al. [13], which is a modified version of Ebert and McBride's method [14], in which errors between rainfall prediction and observation are quantitatively evaluated by the following formula:

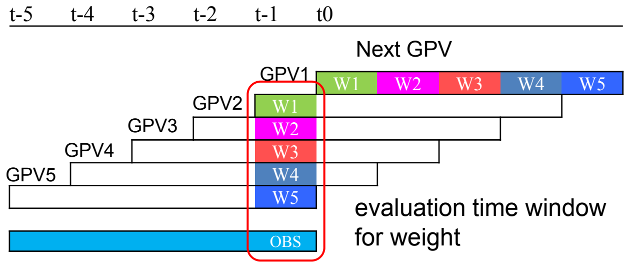

Fig. 2. Schematic of error evaluation. Past GPV (t-5, t-4, ..., t-1) are evaluated against observed rainfall, and the resulting error weight is applied as the weight of uncertainty to the next GPV (t0).

$$\mathrm{FE}_{i,t} = \frac{1}{2}\left[\left(\frac{\mathrm{HI}_{i,\mathrm{QPF}}}{\mathrm{HI}_{i,\mathrm{OBS}}}\right) + \left(\frac{\mathrm{MI}_{i,\mathrm{QPF}}}{\mathrm{MI}_{i,\mathrm{OBS}}}\right)\right] \quad . \; . \; . \quad (1)$$

where FE is the forecast error (-), HI is the highest intensity of rainfall (mm), and MI is the mean intensity of rainfall (mm). The subscripts i and t indicate the evaluation zone index (see below) and evaluation time window, respectively. The subscript QPF indicates the quantitative precipitation forecast, and the subscript OBS indicates the observed radar rainfall.

As expressed by the right-hand side of the equation, when FE is greater than 1, QPF overestimates rainfall. For FE values less than 1 and greater than 0, QPF underestimates rainfall (see upper two rows in **Table 1**).

Saavedra et al. [13] introduced the concept of differently sized zones over the river basin, so that the displacement of rainfall could be captured within each time step t in Eq. (1). Firstly, the upper regions of the Aimata-, Sonohara-, and Fujiwara-dam basins are defined as the smallest zones (**Fig. 1**). In the next level, three circular zones of different radii are considered, such that the movement of the rainfall band is captured within the circles. Finally, the domain encompassing all zones is considered the largest zone. With consideration for errors in both the intensity and spatial displacement of precipitation, forecast errors are fed back to hydrological model as uncertainty in forcing.

According to Saavedra et al. [13], the evaluation of forecast error is performed at each QPF issuance (**Fig. 2**) and the error is converted into a perturbation weight using the conversion table shown in **Table 1**. Perturbation weights are empirically derived after Saavedra et al. [13] to reflect past QPF accuracy. If the QPF in the previous time step showed good agreement with observations in terms of intensity, location, and extent, low uncertainty is considered and minimum weights are applied. On the other hand, if the QPF showed overestimation or underestimation, larger weights are applied to reflect higher uncertainty. The derived weight is then used as perturbation noise following a Gaussian distribution [15] to produce the ensemble of quantitative precipitation forecast, EQPF:

$$\mathrm{EQPF}(x,y)_t = \max\{\mathrm{QPF}(x,y)\{1+A\,\varepsilon N(0,1)\,wi_{sub} + [B\,\varepsilon N(0,1)\,wi_{tot}]\},0\} \quad (2)$$

where x and y are spatial coordinates in horizontal directions, t is the lead time step, ε is 0.33 (corresponding to the exceedance probability 0.0014 [13]), $N(0,1)$ is the standard normal distribution, and wi_{sub} and wi_{tot} represent the perturbation weights for the dam's sub-basins and for the entire basin, circular buffer regions, and entire model domain, respectively. Terms A and B are ratio coefficients that assign superiority in weight to either the sub-basin or the full model domain; their sum is equal to 1. Following Saavedra et al. [13], 60% of the weight is given to A (sub-basin) and the rest of 40% is given to B (entire domain). Eq. (2) is used repeatedly to generate a total of 51 ensemble members.

3.3. Ensemble Streamflow Prediction (ESP) Model

WEB-DHM is used in the ESP model for simulating flood forecasts. The ESP model takes the output from the real-time hydrological model as its initial conditions and applies the 51 members of perturbed precipitation from the ensemble precipitation forecast as forcing. The real-time hydrological and ESP models differ in scope; the former estimates the physical state of the current basin, while the latter estimates flood discharge based on EQPF forcing. During the lead time simulation, outflow from the dam is set equivalent to inflow, because the interventions in actual operations are difficult to predict. In the present system, flood forecasting is performed each time the GPV is issued. Hence, the system produces 51 ESPs every 3 h, with 15 h lead time.

3.4. Virtual Reservoir Simulator Model

The reservoir simulator model is a variation of the ESP model; it also uses output from the real-time hydrological model as the initial conditions. It differs from the ESP model in taking the original QPF as forcing, as well as including a dam operation component. This component allows model users to set dam-release scenarios, and the resulting changes in the stored water and river discharge downstream can be calculated. In actual conditions, dam release must strictly follow operation rules to manage the river environment and achieve flood control. However, in this study, we provide hypothetical release scenarios so that reservoir managers can experiment with hypothetical cases. This allows managers to foresee the possible effects of their hypothetical release on the stored water level in reservoirs and downstream river discharge. The dam release scenario is modeled by inflow multiplication factors ranging from 0 to 2. The multiplication factor of 0 means no release; 1 means the outflow is equivalent to inflow; 2 means the outflow is twice the inflow. Multiplication factors are provided from 0 to 2 with increments of 0.25. The rationale for providing an outflow larger than the inflow is that it demonstrates a hypothetical a priori dam release operation before the onset of flooding.

In this research, the three reservoirs of the Aimata-, Sonohara-, and Fujiwara-dams are considered. There are several combinations of reservoir operations from the three reservoirs, and the effectiveness of each scenario is measured by the volumetric score S (m^3) yielded by the equation below:

$$S = \mathrm{PFV} + \sum_{i=1}^{3} \mathrm{RFV}_i \quad (3)$$

where PFV (m^3) is the flood volume at Maebashi integrated over forecast time, and RFV (m^3) are the reservoir free volumes. The subscript i denotes the three reservoirs of Aimata-, Sonohara-, and Fujiwara-dam. Ideally, it is best to achieve low S, which implies minimum flooding downstream and higher reservoir levels.

3.5. Data Archive Integration

In order to realize flood prediction using these models, a system that links data and models online and automates the input/output process among models is needed. In this study, an integrated analysis system is developed, which has a built-in Geographic Information System (GIS) function to convert point-observed data or grid-discretized data into the format required by WEB-DHM. Program execution, data transfer, and synchronization of models are also controlled by this system. The integrated system is embedded into the Data Integration and Archive System (DIAS), a Japanese national project for integrating and analyzing various geo-scientific data. The use of geo-scientific data, such as radar rainfall data or QPF products, involves several preprocessing steps, e.g., data retrieval, decoding, and reformatting, among others. These procedures cause difficulties in applying data for real-time simulations. The integration of the system into DIAS provides an ideal environment for real-time simulation, as the models can access new data directly without a time delay, and the simulated results can also be provided externally. Thus, the flow of data from retrieval to the visualization of results can proceed flawlessly.

4. Data

The models used in this study are based on previous studies [11] and thus the data required for model setup, such as ground slope, soil type, and slope length, are essentially the same. Therefore, detailed descriptions of data are omitted here, but they are available

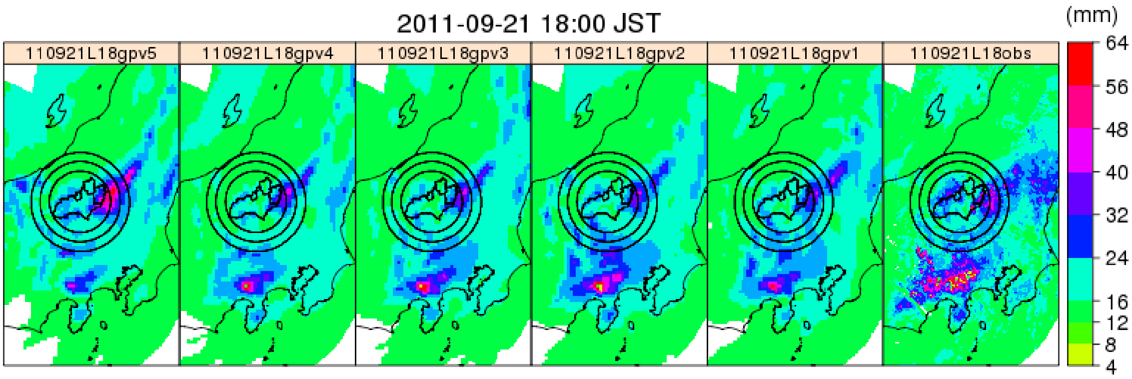

Fig. 3. Comparison of GPV and observed rainfall for GPV issued at 2011-9-21 18:00 JST. The six panels from left to right show the 3-h cumulative rainfall calculated for 15, 12, 9, 6, and 3 hours previous and the corresponding observed rainfall.

in [11]. There are, however, some differences in this study, because meteorological forcing data are produced online by the database-integrated system. Air temperature, wind velocity, and sunshine duration are obtained from the Automated Meteorological Data Acquisition System (AMeDAS) through the National Agriculture and Food Research Organization (NARO). The observed relative humidity and air pressure are not available in real time; hence, predicted values from Meso-Scale Model (MSM) GPV are used instead of observations. These meteorological forcing factors are gridded and combined for application to WEB-DHM.

Regarding precipitation, C-band radar rainfall from MLIT is used for the real-time hydrological model and evaluation of forecast errors. As for QPF, MSM-GPV (precipitation forecast is denoted as GPV here after) is used for forecast values. All data is stored in DIAS on a real-time basis.

5. Results and Discussion

5.1. Evaluation of GPV by Observed Rainfall

Figure 3 shows examples of comparisons between the GPV and observed rainfall during Typhoon Roke in 2011. The rightmost panel shows the 3-h accumulated rainfall from C-band radar rainfall data; the other five panels show the 3-h accumulated rainfall of GPV, which were issued at five different times but corresponded to the same 3-h period (see **Fig. 2** for visualized scheme).

When the spatial pattern of the accumulated rainfall is compared throughout the rectangular domain, all five GPV show good agreement with the observation. However, when the GPV is compared at a sub-basin scale (i.e., within the three circular outlines), it is found that the forecast misses rainfall. A rainfall group located upstream of the Aimata dam basin (see **Fig. 1**) is not found in GPV. Therefore, even if the placement of rainfall from GPV shows good matches with observation, the application of the original GPV may yield underestimates of river discharges at the sub-basin scale.

This issue is addressed by considering uncertainties in

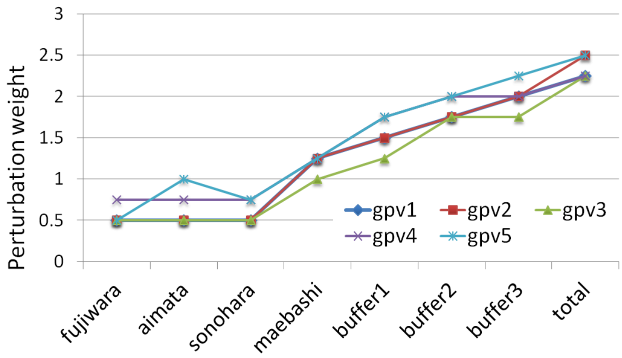

Fig. 4. Perturbation weight converted from error evaluation. The time corresponds to **Fig. 3**.

the precipitation forecast. **Fig. 4** shows the perturbation weight, converted from forecast error in **Table 1**. Generally, the weight is larger for less accurate forecasts and smaller for more accurate results (see 3.2). The perturbation weight of the Aimata-dam basin is higher than those of the Fujiwara- and Sonohara-dam basins, indicating that a wider range of uncertainty is applied to this basin with larger weight. The weight varies according to the accuracy of GPV; it does not always and necessarily assign larger uncertainty to a particular sub-basin.

Figure 4 also shows that larger evaluation zones are considered with larger weights (vertical direction in **Table 1**). This reflects the fact that, for a relatively large river basin, river discharge takes more travel time, and therefore the uncertainty in the flood increases as it flows downstream.

5.2. ESP in Three Typhoon Cases

Figure 5 shows the results of ESP with a) Typhoon Talas in September 2011, b) Typhoon Roke in September 2011, and c) Typhoon Man-Yi in September 2013. In each figure, the solid line indicates the observed river discharge reported from MLIT and the thin lines show the predicted streamflow in which different EQPF members are applied as forcing. Simulations are performed every 3 h when the new GPV is issued; the lead time of the forecast is equiv-

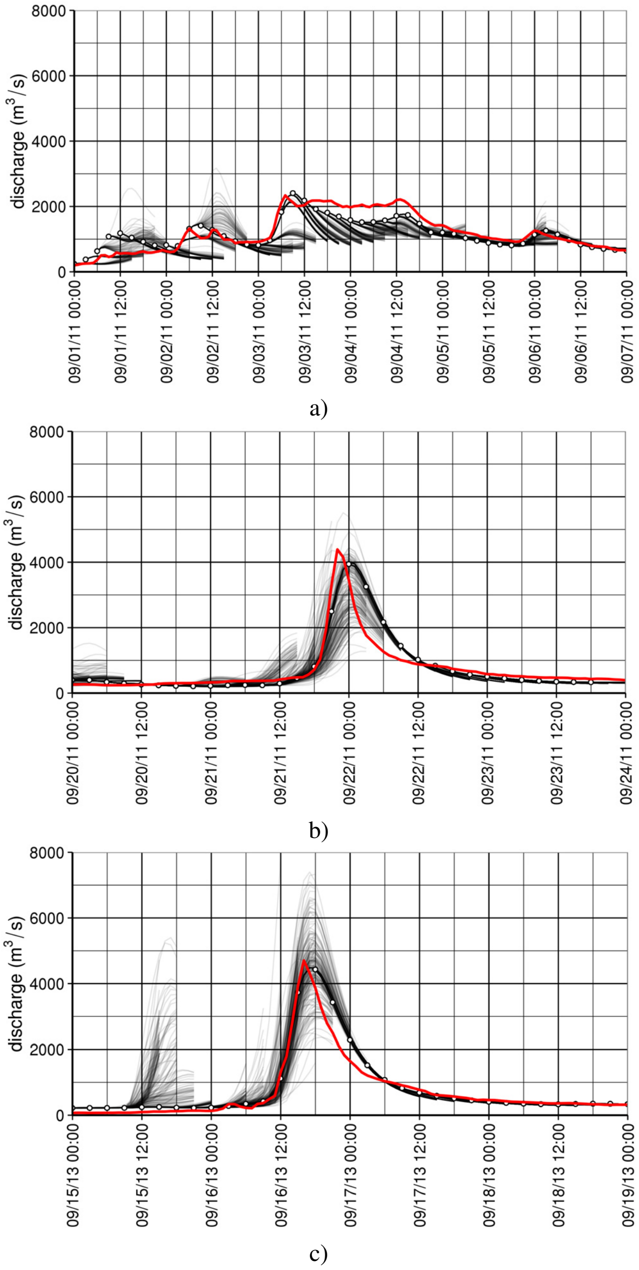

Fig. 5. Comparison of observed river discharge (single line) and ESP (group of thin lines originating from open white circles) of a) Typhoon Talas in 2011, b) Typhoon Roke in 2011, c) Typhoon Man-Yi in 2013.

alent to the forecast time length of GPV, i.e., 15 h. At the starting time of each simulation, as denoted by open white circles, the initial condition of the basin is updated hourly by the real-time hydrological model, which is based on observed climatology. Hence, the most recent condition of the basin (soil moisture content, groundwater storage, and river discharges) is reflected each time the ESP simulation starts.

In the case of Typhoon Talas (**Fig. 5a**), it is found that the rise of the river discharge is slower in the simulation than was observed. However, this slow response is moderated by the updated initial condition; for example, see the discharges from 9/3/2011 0:00 to 12:00. For Typhoon Roke (**Fig. 5b**), ESP overestimates the onset of the flood event at around 9/21 12:00, but the overestimate is revised when the new ESP simulation begins 3 h later with the next GPV issuance. In the case of Typhoon Man-Yi (**Fig. 5c**), ESP highly overestimates the river discharges, but these are revised as time progresses and the observed flood data is well contained within the range of ESP, from the rise to peak discharges.

All in all, it is found that ensemble spread may capture the observed discharges, but underestimation or overestimation may occur, mainly from the accuracy of the applied rainfall forecast. It is also found that, while WEB-DHM can improve the run-off generation process, further improvement is needed for the initial conditions of river discharges, which appear to cause some discrepancy (between open circles and solid lines).

5.3. Virtual Reservoir Simulator

Figure 6 shows the results of the virtual reservoir simulator model for the flood event of Typhoon Roke (corresponding ESP in **Fig. 5b**). The figure shows a snapshot of the dam state at 15:00 on September 21, 2011, with a lead time of 15 h.

The three upper graphs show the time evolutions of the water levels in the Aimata (top left), Fujiwara (top right), and Sonohara dams (middle right). The three horizontal lines in the reservoir graphs indicate the normal water level, normal flood-season level, and the lower water level. The lower three graphs show the time evolutions of the total stored water volume in the three reservoirs (lower left), the river discharge at the basin outlet of Maebashi (lower middle), and the corresponding water level at the outlet (lower right). The water levels are derived by applying the H-Q rating curve to the simulated discharge. The water level at the outlet point also includes four horizontal lines. From the bottom, these correspond to the levels of stand-by for flood fighting, flood watch, evacuation alert, and flood danger, respectively.

While the reservoir inflow is estimated by WEB-DHM as the average values of the GPV ensemble used as forcing, different reservoir release scenarios can be chosen. These are shown by nine water levels corresponding to multiplication factors ranging from 0 to 2 at increments of 0.25. In Japan, rigid rules exist for dam operations to ensure safety downstream and at the dam, and all reservoir managers must follow these rules under all circumstances. The advantage of the virtual reservoir simulator here is that, while recognizing the rules, the simulator provides managers with the flexibility to experiment with dam release so they can learn the most beneficial operation through trial operations. All graphs are drawn on an interactive web page and hence users of the system can choose any multiplication factor by clicking the water levels. When a user changes the water release scenarios, the corresponding results in the total stored water volume, discharge, water level at the river outlet, and volumetric score S are drawn immediately on the web page. As S is

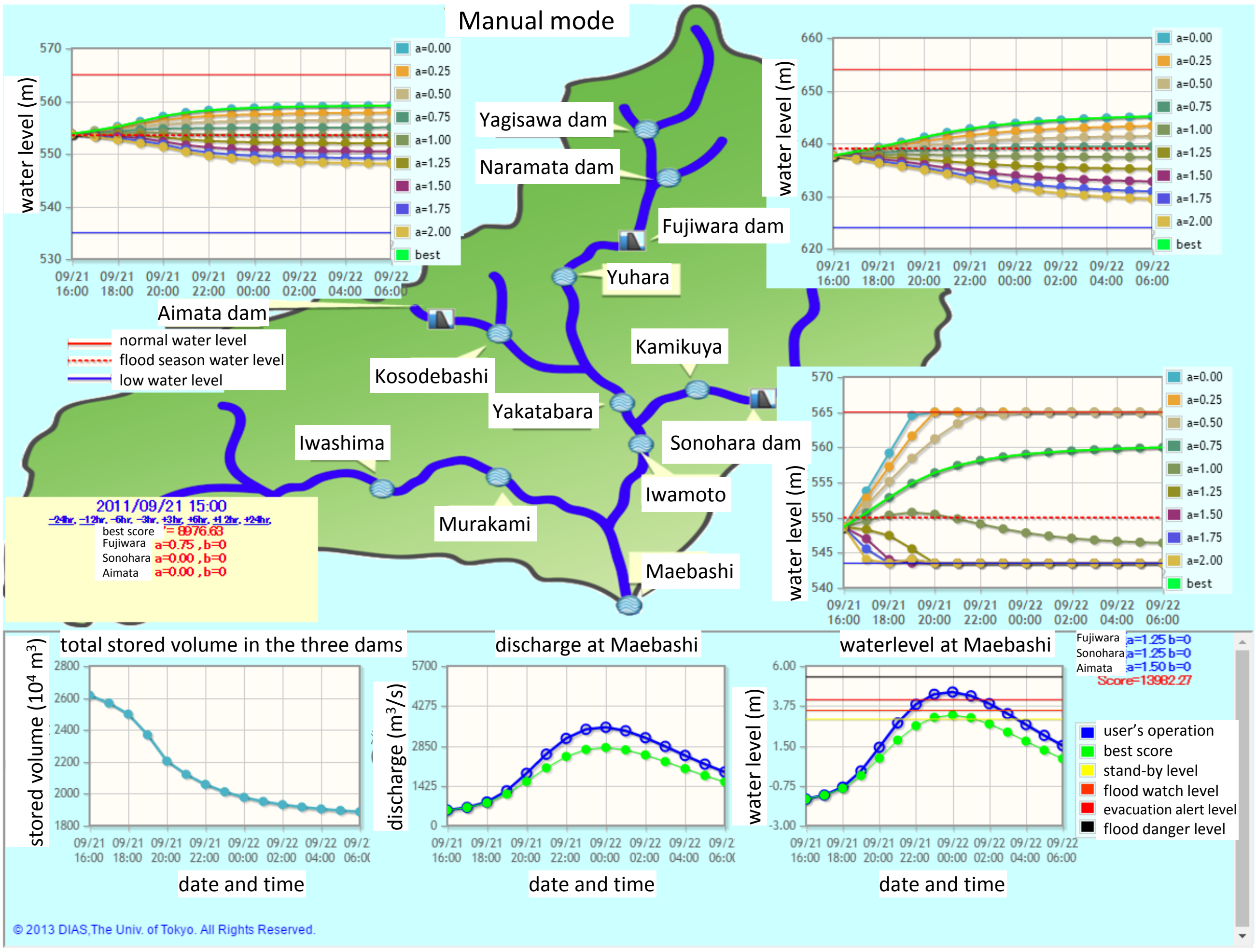

Fig. 6. Screenshot of the virtual reservoir simulator model. The results are linked to the DIAS data archive and users of the system can perform virtual simulations of the reservoirs interactively.

the sum of the free reservoir volumes of the three dams and the integrated flood volume at Maebashi, a smaller S value is preferable because it indicates that more water is stored in reservoirs and the flood discharge downstream is lower (see 3.4). Choices of water release scenarios are available for all three reservoirs and users can try different combinations of water releases. The currently chosen scenarios show $S = 13982$ m^3. Meanwhile, the system provides the best operation practice evaluated from the best score, in this case 8977 m^3, which is estimated by simulating all combinations of release scenarios. The corresponding lines are drawn on top of each graph in light colors (excepting the total reservoir volume).

In this way, the system provides managers with the opportunity to foresee how certain operations would reduce flood volume while maintaining reservoir volume, with reference to the best scenario. As described earlier, the release scenarios provided by the simulation are hypothetical and exempted from the rigidly defined rules, and therefore the implementation of operational rules is necessary when applying the simulator in actual dam operation.

6. Conclusion

As described in the introduction, scientific problems in flood forecasting include the accuracy of estimating initial conditions and the consideration of QPF uncertainty. In addition, the practical problem of transferring forecast information to the corresponding authorities who make decisions under critical conditions must be solved.

In this research, the authors addressed these issues by developing a data archive and model integrated system, which combines advanced hydrological models with the largest data archive available in geosciences. A virtual reservoir simulator, which provides an interactive means for exploring hypothetical dam operations, was developed, allowing users to experiment with how operations may affect downstream river flooding and water stored in reservoirs. With integration into the DIAS data-archive, all these models can be simulated on a real-time basis.

To our best knowledge, no other similar integrated data archive and hydrological modeling approach exists that permits the proactive use of forecast information, which can assist authorities in making decisions with higher degrees of confidence. We note that dam operators may wish to rely on observed data rather than QPF because of its uncertainty. In this study, we showed that integrating real-time reservoir inflow and water volume with QPF makes it possible to increase confidence in QPF for evaluating the impact of flood events. Because flood control and water resources management are closely related, it is anticipated that scope of the system is not limited to flood control, but has potential in many applications of water resources management such as hydroelectric power generation. One ongoing project, in which the current system is applied to a hydro-power dam, supports an electric company, demonstrating another important aspect of how advances in engineering can be societally implemented.

Issues remain regarding the discrepancy in the modeled and observed discharges and the uncertainty in applied QPF. Errors in modeled discharges can be attributed to runoff generation and river routing processes. The present study addressed the former issue by applying a land-surface-model coupled with a hydrological model. To overcome the latter issue, further development is necessary, such as the assimilation of observed discharges. Improvement of QPF itself is beyond the scope of the present study. However, the application of recent data assimilation methods, such as the integration of cloud microphysics [16], could improve the forecast accuracy.

The virtual reservoir simulator shows the most beneficial release scenario under a specific condition. It is necessary to incorporate existing safety regulations for water release, which constrains certain operation, to derive the best-case scenario in real situations. In addition, the simulator currently uses the averaged information from ensemble discharges. It is necessary to further introduce forecast uncertainty, information on which is available in the ensemble spread, to guide and restrict release operations based on statistics.

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References:

[1] H. Kardhana and A. Mano, "Uncertainty Evaluation in a Flood Forecasting Model Using JMA Numerical Weather Prediction," J. of Disaster Research, Vol.4, No.4, pp. 272-277, 2009.

[2] Y. Sugihara, S. Imagama, N. Matsunaga, and Y. Hisada, "Numerical Experiments on Spatially Averaged Precipitation in Heavy Rainfall Event Using the WRF Model," J. of Disaster Research, Vol.10, No.3, pp. 436-447, 2015.

[3] Y. Shibuo, E. Ikoma, O. Saavedra, L. Wang, P. Koudelova, M. Kitsuregawa, and T. Koike, "Development of operational realtime ensemble flood forecast system," Annual J. of Hydraulic Engineering, JSCE, B1 (Hydraulic Engineering), Vol.70, No.4, pp. I_397-I_402, 2014.

[4] T. Sayama, Y. Tachikawa, and K. Taara, " Data assimilation of a distributed rainfall-runoff prediction system by Kalman filter with bias correction," Doboku Gakkai Ronbunshuu B, Vol.64, No.4, pp. 226-239, 2008.

[5] Y. Tachikawa, J. Sudo, M. Shiba, K. Yorozu, and S. Kim, " Development of a real-time river stage forecasting method using a particle filter," JSCE, B1 (Hydraulic Engineering), Vol.67, No.4, pp. I_511-I_516, 2011.

[6] Q. Xiao and J. Sun, "Multiple radar data assimilation and short-range QPF of a squall line observed during IHOP_2002," Mon. Wea. Rev., 135, pp. 3318-3404, 2007.

[7] E. M. Sukovich, F. Martin Ralph, F. E. Barthold, D. W. Reynolds, and D. R. Novak, "Extreme quantitative precipitation forecast performance at the weather prediction center from 2001 to 2011," Wea. Forecasting, Vol.29, pp. 894-911, 2014.

[8] L. Wang, T. Koike, K. Yang, T. K. Jackson, R. Bindlish, and D. Yang, "Development of a distributed biosphere hydrological model and its evaluation with the Southern Great Plains Experiments (SGP97 and SGP99)," J. Geophys. Res., Vol.114, D08107, doi:10.1029/2008JD010800, 2009.

[9] D. Yang, T. Koike, and H. Tanizawa, "Application of a distributed hydrological model and weather radar observations for flood management in the upper Tone River of Japan," Hydrol. Process., Vol.18, pp. 3119-3132, 2004.

[10] P. J. Sellers, D. A. Randall, G. J. Collatz, J. A. Berry, C. B. Field, D. A. Dazlich, C. Zhang, G.D. Collelo, and L. Bounoua, "A revised land surface parameterization (SiB2) for atmospheric GCMs. 1. Model formulation," J. Climate, Vol.9, pp. 676-705, 1996.

[11] L. Wang, T. Koike, K. Yang, and P. J.-F. Yeh, "Assessment of a distributed biosphere hydrological model against streamflow and MODIS land surface temperature in the upper Tone River Basin," J. Hydrol., Vol.377, pp. 21-34, 2009.

[12] M. R. J. Turner, J. P. Walker, and P. R. Oke, "Ensemble member generation for sequential data assimilation," Remote Sens. Environ., Vol.112, pp. 1421-1433, 2008.

[13] O. Saavedra Valeriano, T. Koike, K. Yang, T. Graf, X. Li, L. Wang, and X. Han, "Decision support for dam release during floods using a distributed biosphere hydrological model driven by quantitative precipitation forecasts," Water Resour. Res., Vol.46, W10544, 2010.

[14] E. E. Ebert, and J. L. McBride, "Verification of precipitation in weather systems: Determination of systematic errors," J. Hydrol., Vol.239, pp. 179-202, 2000.

[15] P. Goovaerts," Geostatistics for Natural Resources Evaluation," p. 483, Oxford Univ. Press, New York, 1997.

[16] R. Seto, T. Koike, and M. Rasmy, "Development of a Satellite Land and Cloud Data Assimilation System Coupled with Wrf, and its Application to Kanto Area," JSCE, B1 (Hydraulic Engineering), Vol.70, No.4, pp. I_535-I_540, 2014.

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- Y. Shibuo, and S. Kanae, "Comparisons of Bias Correction Methods for Climate Model's Daily Precipitation – From a Heavy Rainfall Perspective," JSCE 54, pp. 235-240, 2010.
- Y. Shibuo, J. Jarsjo, and G. Destouni, "Hydrological responses to climate change and irrigation in the Aral Sea drainage basin," Geophys. Res. Lett., Vol.34, L21406, doi:10.1029/2007GL031465, 2007.

Academic Societies & Scientific Organizations:
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- E. Ikoma, M. Oyanagi, H. Sano, K. Tamagawa, T. Koike, and M. Kitsuregawa, "Development and operation of real-time earth observation data archiving and processing system on DIAS," Japan Geoscience Union Annual Meeting 2015, M-GI37, 2015.

Academic Societies & Scientific Organizations:
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- O. Saavedra Valeriano, T. Koike, M. Ryo and S. Kanae, "Real Time Flood Control using Quantitative Precipitation Forecast and Ensemble Approach in Rainfall Forecasting," book chapter in "Rainfall Forecasting" Tommy Wong (ed), ISBN: 978-1-61942-134-9, Nova Science Publishers, pp. 233-276, 2012.

Academic Societies & Scientific Organizations:
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- L. Wang, T. Koike, K. Yang, and P. Yeh, "Assessment of a distributed biosphere hydrological model against streamflows and MODIS land surface temperature in the upper Tone River Basin," J. of Hydrology, 377, pp. 21-34, 2009.
- L. Wang, T. Koike, K. Yang, T. Jackson, R. Bindlish, and D. Yang, "Development of a distributed biosphere hydrological model and its evaluation with the Southern Great Plains Experiments (SGP97 and SGP99)," J. of Geophysical Research-Atmospheres, 114, D08107, doi:10.1029/2008JD010800, 2009.
- L. Wang, T. Koike, D. Yang, and K. Yang, "Improving the hydrology of the Simple Biosphere Model 2 and its evaluation within the framework of a distributed hydrological model," Hydrological Sciences J., Vol.54, No.6, pp. 989-1006, 2009.

Academic Societies & Scientific Organizations:
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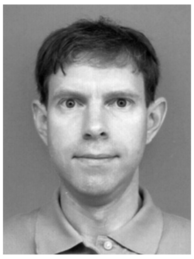

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• N. Kaji and M. Kitsuregawa, "2. Building Lexicon for Sentiment Analysis from Massive Collection of HTML Documents," Proceedings of the 2007 Joint Conf. on Empirical Methods in Natural Language Proc. and Computational Natural Language Learning (EMNLP-CoNLL), pp. 1075–1083, Prague, Czech Republic. Association for Computational Linguistics, 2007.

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• T. Koike, P. Koudelova, P. A. Jaranilla-Sanchez, A. M. Bhatti, C. T. Nyunt and K. Tamagawa, "River management system development in Asia based on data integration and analysis system (DIAS) under GEOSS," Science China, Earth Sciences, Vol.57, No,1, 20, doi:10.1007/s11430-014-5004-3,2014.
• M. Rasmy, T. Koike, X. Li, and K. Yang, "Application of multi-frequency passive microwave observations and data assimilation methods for enhancing numerical weather forecast in Niger, Africa," Remote Sens., Vol.6, No.6, pp. 5306-5324, doi:10.3390/rs6065306, 2014.

Academic Societies & Scientific Organizations:
• Japan Society of Civil Engineers (JSCE)
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