Flood Forecasting in Small and Medium-Sized Rivers

a) Introduction

In recent years, increasingly frequent and intense heavy rainfall events have caused significant human and physical damage from water-related disasters in Japan and around the world. In Japan, these impacts are evident not only along major rivers but also along small and medium-sized rivers managed by prefectures and designated cities. Because these smaller rivers have limited basin areas and water levels rise quickly after rainfall begins, it is difficult to secure adequate lead time for residents to make evacuation decisions. In addition, many of these rivers lack sufficient hydrological data, such as water levels and discharge, as well as detailed channel-cross-section information, making it challenging to introduce conventional, highly sophisticated flood-forecasting systems. As climate change driven by global warming is expected to increase the frequency of flooding, the development of water-level forecasting systems that can predict water levels even a few hours ahead has become an urgent priority to ensure safe evacuation.

To address this urgent need, PWRI worked to develop a real-time water-level forecasting system for small and medium-sized rivers, with support from the Cabinet Office's Public/Private R&D Investment Strategic Expansion Program (PRISM) from FY2018 to FY2022. PWRI designed the system to predict when river water levels will reach thresholds requiring resident evacuation up to roughly two hours in advance. Other requirements included applicability to smaller rivers, quick calculations, ease of operation, cost-efficiency, and sufficient accuracy.

A distinctive feature of this research is its strong emphasis on practicality in real-world situations, integrating the entire process – from research and development to on-site demonstration and the preparation of manuals for nationwide deployment – into a single, coherent effort. The following sections provide an overview of the system, and for further details, please refer to the references listed at the end.

b) Overview of the real-time water-level forecasting system

This system consists of the following five main processes (Figure 1):

1. Construction of the base model using the RRI_GUI
2. Initial analysis using default parameters
3. Automatic parameter optimization using the SCE-UA method
4. Water-level data assimilation using a particle filter
5. Real-time computation and distribution on the DIAS platform

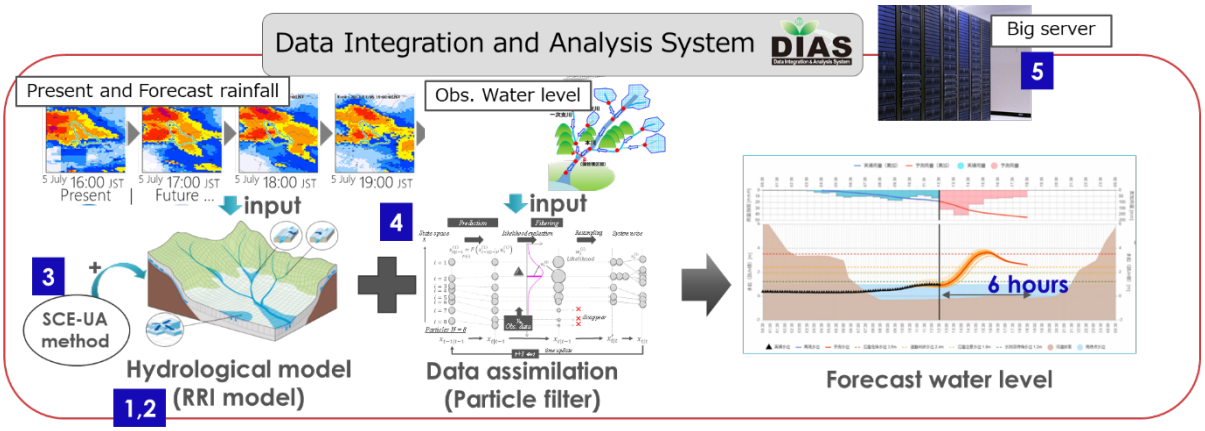


Figure 1 Outline of main system

For rainfall–runoff analysis, the system adopts the open-source Rainfall–Runoff–Inundation (RRI) model. To make model construction easier – from obtaining terrain and land-use data to building the model itself – we developed a new GUI optimized for compatibility with domestic datasets. The system can use several types of rainfall data provided by the Japan Meteorological Agency, including analyzed rainfall, short-term precipitation forecasts, high-resolution precipitation nowcasts, and ground-based rain-gauge observations. In the model constructed for this study, river cross-sections are represented as rectangular channels, and channel width and depth are determined using regime equations. Using this GUI, a base model is constructed for each river. The default spatial resolution of these base models is 5 arc-seconds.

The system conducts an initial simulation using the default parameters and, based on the results, makes adjustments to the H–Q relationship and reviews the rainfall products. The default parameters consist of general values described in the RRI model manual, as well as average values derived empirically from building models for 200 rivers. The purpose of this step is to identify issues that exist prior to parameter calibration by checking, in particular, the consistency of normal water levels during non-rainfall periods and the responsiveness of the hydrograph to rainfall.

In addition, to reduce the time and effort required for model construction, the parameter-optimization method SCE-UA, developed by Duan et al., is incorporated into the RRI model, enabling automatic calibration using multiple flood events. SCE-UA has greatly improved the efficiency of parameter tuning, which previously required specialized expertise and a substantial amount of time.

In this development, we adopted a particle filter for water-level data assimilation, which serves as a core component of the forecasting system.

The RRI model adopted for this development is not designed to consider water and energy balances such as evapotranspiration. As a result, when real-time forecasting is run continuously over long periods, errors in the initial conditions gradually accumulate and can significantly affect the prediction results. To correct these errors, we incorporated a particle filter, a data-assimilation technology, into the RRI model, enabling sequential correction of calculated water levels using observed water-level data.

As the state variable for sequential correction, we selected the slope water depth hs above the

impermeable layer. This choice reflects both the practical difficulty of directly observing soil moisture conditions in real time and the fact that, within the RRI model, the behavior of slope water depth has a strong influence on the resulting river water levels. Meanwhile, some previous studies have reported applications of particle filters to other state variables, such as the storage volumes of channel cells, indicating room for further improvement in the future.

Because small and medium-sized rivers typically have only a single water-level gauge installed, the system uses the gauge location as the evaluation point, and the correction factor is applied uniformly across the entire basin.

The constructed model was implemented on the Data Integration and Analysis System (DIAS), where it automatically retrieves rainfall and water-level observations and performs real-time water-level forecasting every 30 minutes, providing predictions up to six hours ahead. For input rainfall, the system uses analyzed rainfall for the past three hours from the current time and short-term precipitation forecasts for the subsequent six hours, allowing each run to process a total of nine hours of rainfall data.

When evaluating the accuracy of the water-level forecasts produced by this system, it is necessary to distinguish between errors arising from rainfall-forecast uncertainty and those attributable to the model's reproducibility. For this reason, the accuracy assessment also includes analyses in which observed rainfall is used in place of forecast rainfall.

c) Demonstration results and accuracy evaluation

To apply the water-level forecasting system to small and medium-sized rivers with diverse topographic and land-use characteristics, as shown in Figure 2, we constructed trial real-time forecasting models for 200 rivers across Japan and conducted accuracy evaluations for 291 flood events. As a result, the system achieved forecasts within ±50 cm of the flood-danger level (or an equivalent threshold) at least two hours in advance for 75% of the events.

Furthermore, considering that small catchments often have very short flood-response times, we also evaluated performance using the criterion of "±50 cm accuracy within each basin's flood-arrival time." The results showed that the system was able to achieve that level of accuracy for a cumulative total of 89% of the events (Figure 3).

Figure 4 presents an example in which the constructed model was used to perform real-time water-level forecasting during the July 2020 heavy rainfall event. The figure shows the display generated on DIAS, with future water-level predictions added for verification purposes. The target river is a mid-mountain basin with a catchment area of approximately 60 km², about 70% of which is mountainous terrain. As of 1:30 a.m. on July 14, the system predicted that the water level would reach the flood-danger level at 7:10 a.m., while the actual arrival time was 7:20 a.m., yielding a lead time of 5 hours and 50 minutes.

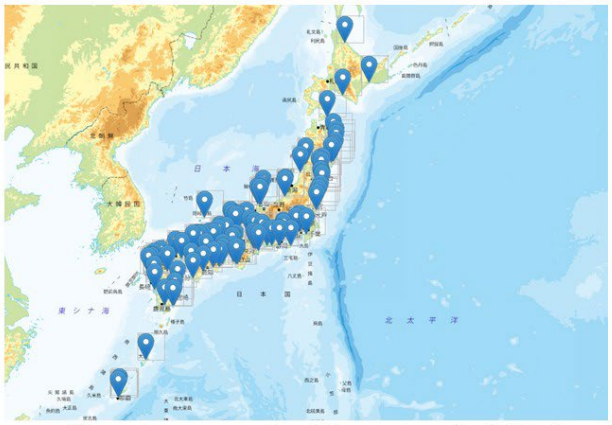


Figure 2　Location of applied medium-sized rivers

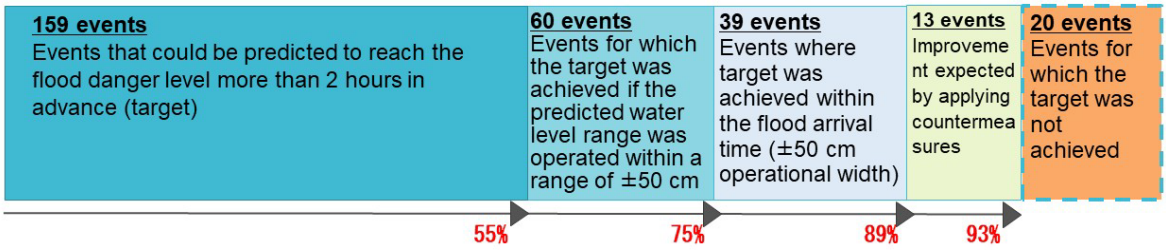


Figure 3　Result of accuracy check

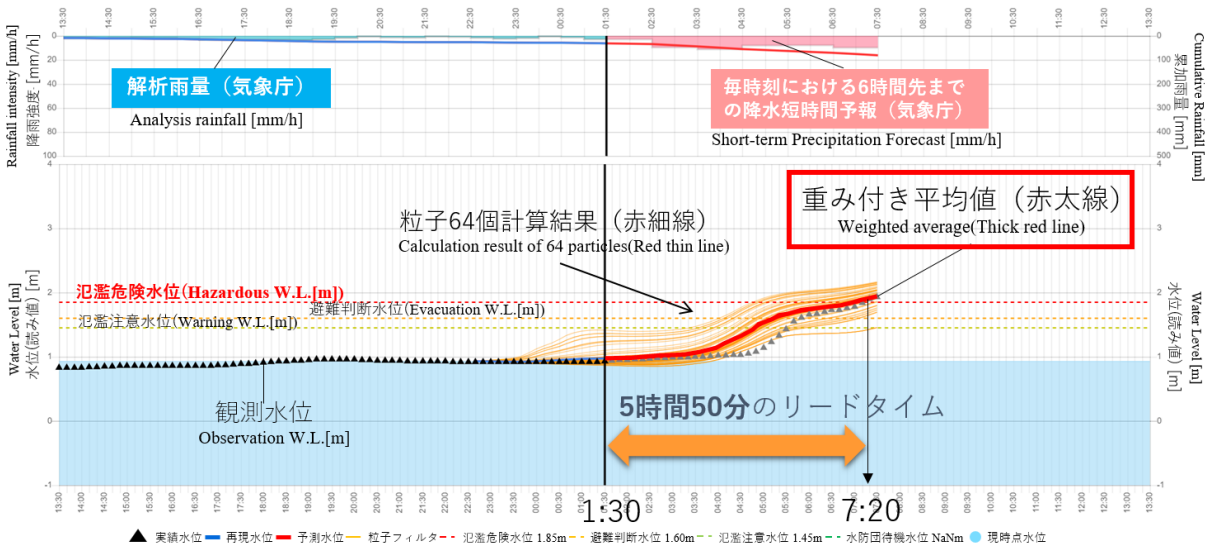


Figure 4　Real-time water-level forecasting calculation results at 1:30 on July 14, 2020, in a typical mountainous river with a basin area of about 60 km2, out of which 70% is in the mountainous area.

b)　Development of the model building manual and nationwide deployment

The knowledge gained through the construction and validation of models for 200 rivers was organized

into a comprehensive manual for building flood forecasting models for small and medium-sized rivers. The manual outlines a standard model that can be built with only the essential functions, along with a set of optional components, which can be selected according to the characteristics of each river.

For rivers lacking water-level data from past flood events, the manual presents a method for identifying similar basins using principal component analysis based on factors such as catchment area and land-use composition, and then transferring parameters from those analogous basins. It also summarizes recommended approaches for addressing practical challenges encountered in the field, including small catchments, anthropogenic flow fluctuations, and observation stations affected by backwater or tidal influences.
(Manual for Flood Forecasting Model Building for small and medium-sized rivers: https://www.pwri.go.jp/icharm/research/articles/project-prism_manual_j.html)

e) Conclusion

In this study, we developed a real-time water-level forecasting system that is both easy to operate and highly reproducible by combining the RRI model with automatic parameter optimization using the SCE-UA method and water-level data assimilation using a particle filter. Demonstrations conducted for 200 rivers across Japan showed that the system achieved forecasts at least two hours in advance for approximately 75% of the events, and met the accuracy target for roughly 90% of the events when evaluated against each basin's flood-arrival time.

Moreover, this work extends beyond research and development, providing a foundation for practical implementation in rivers with diverse sizes and characteristics through the development of a manual for model construction and on-site installation. Widespread adoption of this technology in regions with small and medium-sized rivers is expected to support timely evacuation and help minimize flood-related damage.

Reference

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