10th International Conference on Hydroinformatics
HIC 2012, Hamburg, GERMANY

FLOOD RISK ASSESSMENT SYSTEM FOR MAJOR METROPOLITAN AREAS IN JAPAN

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We integrated a geographic information system (GIS) and modeling environment and assessed the effects of this integration on simulating large-scale floods in metropolitan areas. We describe graphical user interfaces enabled by this integration and how this facilitates the preparation of the simulation models of a large river system with many flood control facilities. We focus on the Tone river system, which has the largest catchment area in Japan. Errors of simulated peak water levels of a past high water event (Typhoon Fitow, 2007) at ten gauging stations were less than or equal to 0.4 m. A possible flood event with a 200-year return period was simulated over 13 hours on a PC server. We conclude that the integration not only facilitates the preparation of the simulation models but also enables fast calculation with practical accuracy on a conventional computer.

1. INTRODUCTION

A large-scale flood is a complex phenomenon composed of many elemental phenomena and their interactions; e.g., rivers, floodways, dams, and detention ponds. A large river system consists of many confluents and diversions. It has many flood control facilities located along its course. Its flow is artificially controlled by dams and detention ponds.

To simulate a flood, we need to describe many elemental phenomena and their interactions by using many numerical models and their couplings. We usually generate models, which involves describing elemental phenomena as variables and dominant equations, discretizing time and space, populating data into those variables, and adjusting the equation parameters. We then couple the models, which involves describing interactions as variables and dominant equations and create relationship among discretized time and space of models. Finally we validate the integrated models, which involve simulating the target phenomenon, comparing the results with those from observation, and adjusting the models and their couplings. To accurately simulate a large-scale flood, we need to generate many models. The more models used, the more coupling requires. Thus, preparing a model for a large-scale flood is a time consuming procedure for a researcher.

Research has been done on large-scale flood simulations for mitigating disasters. For example, the Japanese Cabinet Office [1] simulated possible flood disasters in the Tokyo metropolitan area caused by levee failures along the Tone and Ara rivers, and proposed concrete and detailed countermeasures. A method which facilitates preparation of such simulations would contribute to disaster mitigation planning in various cities. From a practical viewpoint, high accuracy and short calculation time on a conventional computer are also important.

Integration of a geographic information system (GIS) and modeling environment is effective in facilitating simulation preparation and increasing calculation speed. Martin et al. [2] reviewed 36 state-of-the-art modeling software products and found that most are composed of two different systems: a GIS and modeling environment. They suggested that an ideal system should manage time series and three-dimensional information and assist in generating models. We found that such integration not only facilitates simulation preparation but also enables automation of model couplings (between a distributed runoff model and an 1D river model and between an 1D river model and a 2D inundation model) and increasing calculation speed by using the dynamic domain defining method, which optimizes the calculation domain of a 2D inundation model [3, 4].

We explain graphical user interfaces enabled by the integration of a GIS and modeling environment, and how it facilitates the preparation of modeling a large river system with many flood control facilities. We discuss the Tone river system, which has the largest catchment area in Japan. We conclude that though the target was a large-scale flood, our integration method effectively facilitates preparing various models and coupling them and enables fast calculation with practical accuracy on a conventional computer. In Section 2, we describe our software and method for model preparation. We discuss the example of the Tone river system in Section 3 and give conclusions in Section 4.

2. MODELING METHOD

Software architecture

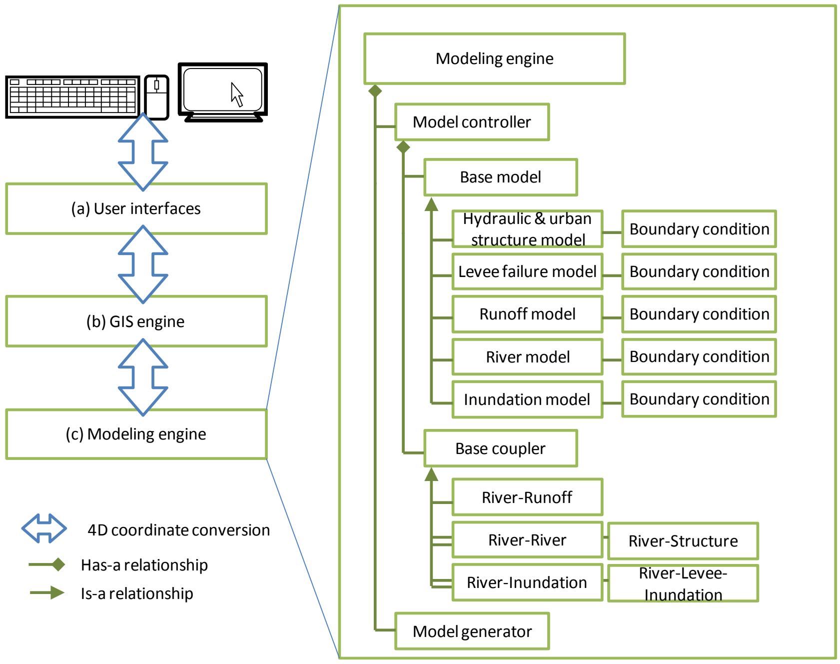

Figure 1. Architecture of our flood simulation software DioVISTA®

Our software, DioVISTA® consists of a Windows-based graphical user interface (GUI), 4D-GIS engine, and modeling engine (Figure 1). The modeling engine includes hydraulic and urban structure, levee failure, runoff, river, and inundation models. It also has couplers between the models. We describe just two couplers; river and detention pond, and river and inundation. Yamaguchi and Ikeda describe other models and couplers [3, 4].

Coupling of river and detention pond models

The coupler for a river and a detention pond describes a section of a river where a side weir and a detention pond are installed. Water from the river flows into the detention pond through the side weir. River flow is described as a 1D unsteady flow using St. Venant Equations. Water level in the detention pond is expressed as a function of water volume in the pond (V-H Curve). The quantity of discharge on the side weir is calculated using the weir equation. Figure 2 shows the interaction among these models. The weir model gets water levels from the river and pond models and calculates the discharge through the weir (Q_{weir}). The value Q_{weir} is subtracted from the corresponding cell of the river model and added to the corresponding pond model.

Figure 3 shows the coupling procedure with our integration method. The procedure is composed of just four steps. We assume that the river and pond models have already been generated but their relationship is not defined. Step 1: the user clicks on the name of the river in the model list in the Model pane and selects “add side weir” from the menu. Step 2: he/she specifies the location of the side weir by clicking the start and end points of the weir on the center line of the river. Step 3: he/she clicks on the detention pond name in the Model pane and selects “add side weir” from the menu. Step 4: he/she clicks on the side weir on the map.

Based on the above procedure, the software generates relationships among the models. In the first and second steps, the relationship between the river and weir (i.e., the river and weir models are connected at the side weir location) are generated. In the third and fourth steps, the relationship between the weir and pond (i.e., the weir and pond models are connected at the side weir location) is generated. The software connects corresponding river, weir and pond models using this information.

Coupling of river and inundation models

The coupler for a river and floodplain describes a section of a river where a levee may be breached. River water flows into the floodplain through the breached levee. Flow in the floodplain is described as a 2D unsteady flow. The quantity of discharge at the breached levee is calculated with the following empirical equations [5]. The levee breaches when the river level reaches its design water level. The width of the breach changes over time.

$$B(t) = B_{max} F(t) \tag{1}$$

$$F(t) = \begin{cases} \frac{1}{2}\left(1 + \frac{t}{T_b}\right) & \text{if} \quad t < T_b \\ 1 & \text{if} \quad t \geq T_b \end{cases} \tag{2}$$

$$B_{max} = A(log_{10} W)^c + B, \tag{3}$$

where $B(t)$ is the width of the breach, W is the width of the river, and the empirical parameters are $T_b = 3600$ [s], $c = 3.8$, $A = 2.0$, and $B = 77$ [m]. The quantity of discharge on the side weir is calculated using the weir equation.

The coupling procedure is simpler than the coupler for a river and a detention pond. Because only one inundation model exists in the simulation, the software can generate a relationship among the models without the third and fourth steps in the procedure of the coupler for a river and a detention pond. We assume that the river and inundation models have already been generated but their relationship is not defined. Step 1: a user clicks on the name of the river in the model list in the Model pane and selects "add levee failure" from the menu. Step 2: he/she clicks on the location of the levee failure.

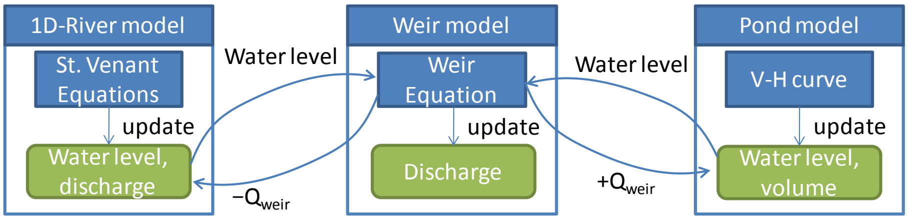

Figure 2. Interaction of river and pond model through weir model

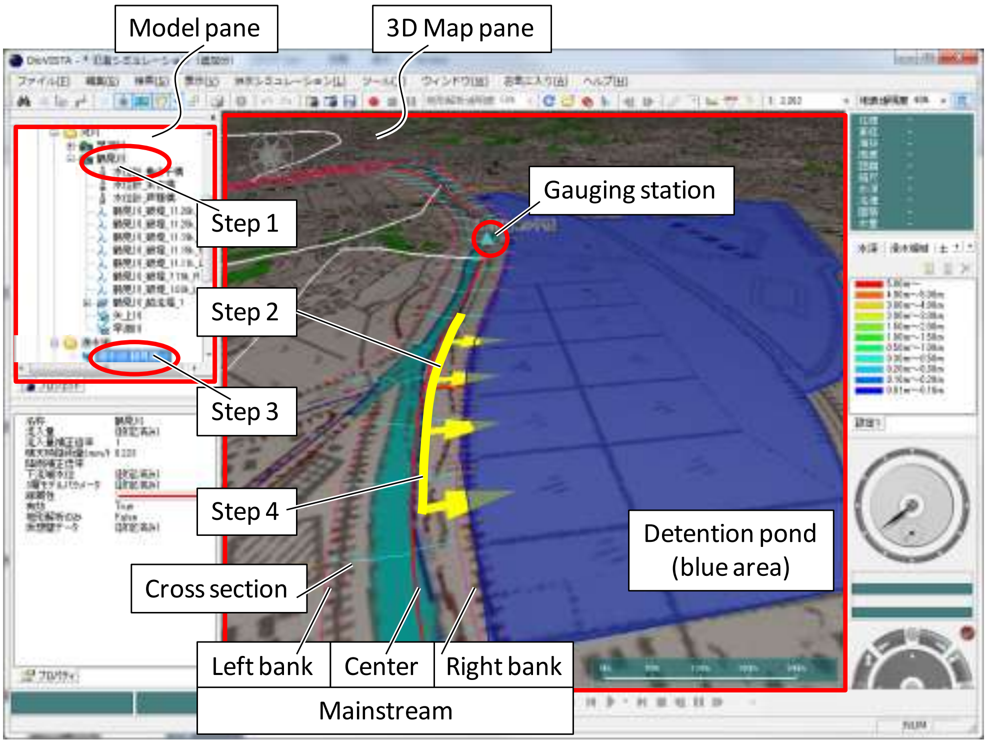

Figure 3. GUI for coupling river and detention pond

3. EXPERIMENT AND RESULTS

We used the software for simulating five river systems in three metropolitan areas (Tokyo, Osaka, and Nagoya) in Japan. The target river systems were the Tone, Ara, Tsurumi, Shonai, and Yodo. We simulated past high water events by using generated models and compared the results with observations. Simulated water levels corresponded well to the observed levels. We then simulated possible floods caused by levee failures and heavy rainfall with certain return periods. We discuss the Tone river system in the following sections.

Past high water event in Tone river system

The Tone river system has the largest catchment area in Japan. A map of the Tone river system is shown in Figure 4. The specifications of the generated model of this river system are listed in Table 1. We simulated significant high water caused by Typhoon Fitow (Typhoon No. 9 in 2007). The target period was 72 hours from 12:00 September 5, 2007.

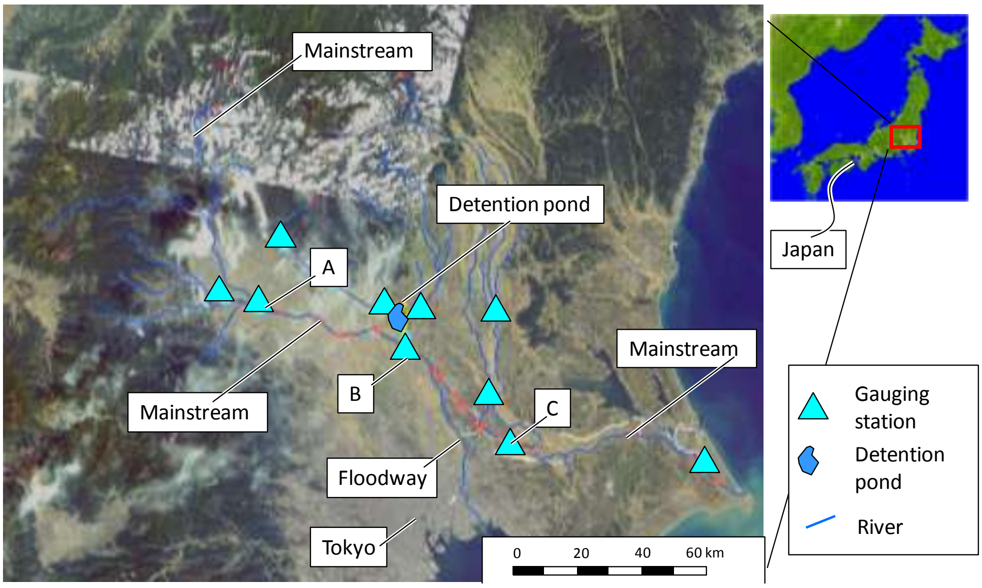

Figure 4. Map of Tone river system

Table 1. Specifications of Tone river system and model

River system	Tone (catchment area: 16,840 km^2)
Modeled rivers	1 mainstream, 20 tributaries
Modeled structures	17 confluences, 2 diversions, 2 detention ponds, 10 dams
Runoff model	Grid size: 100 m x 100 m
River model	Grid size: 50 m
Inundation model	Grid size: 50 m x 50 m
Input data	Precipitation radar data, dam release data, sea level at river mouth

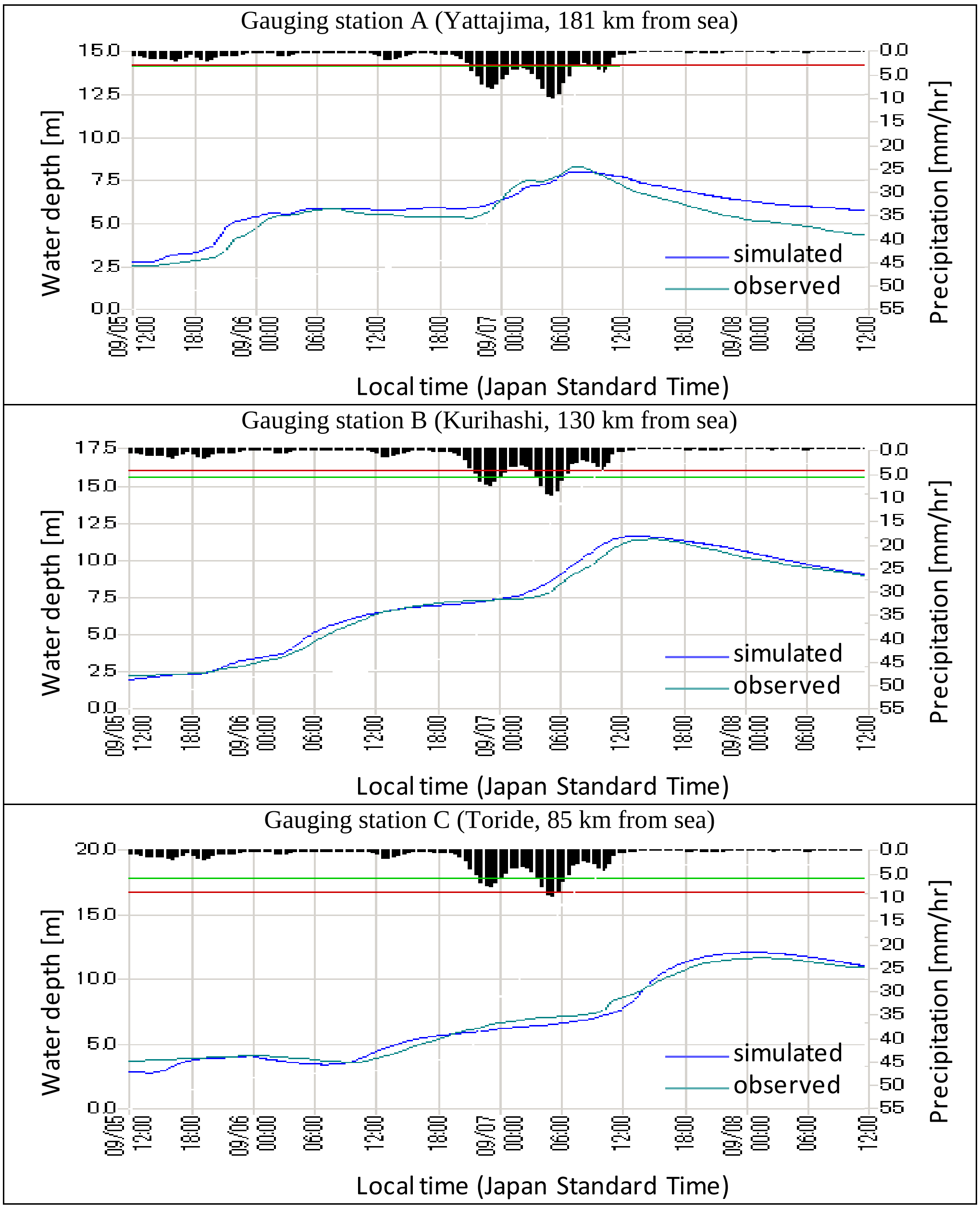

Figure 5. Simulated water depth at mainstream gauging stations

The input data were the time series of rainfall distribution, dam release, and sea level at the river mouth. Rainfall distribution was observed using precipitation radar. The horizontal resolution was 1 km and temporal resolution was 0.5 hours. The data was published by the Japan Meteorological Business Support Center. The dam release data is available at the website of the Database of Dams, Ministry of Land, Infrastructure, Transport and Tourism

(MLIT), Japan. Sea level is available at the website of the Water Information System, MLIT, Japan. Temporal resolutions of the dam release and the sea level data were 1 hour.

The simulated results were compared with those from observation. We used the time series of the water level at ten gauging stations (four gauging stations in the mainstream and six in the tributaries). Data source and temporal resolution were the same as the sea level.

Figure 5 shows the time series of water depth at gauging stations A to C (Figure 4). Gauging station A is located up stream, B is near the diversion of the largest floodway, and C is weakly affected by backwater from the sea. The simulated results corresponded well to those from observations. The errors of the peak water level at the ten gauging stations including A to C were 0 to 0.4 m.

The calculation time for simulating the 72-hour event was about 2 hours by using a computer manufactured in 2009 (OS: Microsoft® Windows® Server 2008 Standard 32 bit, CPU: Intel® Xeon® E5520 @ 2.26 GHz x 2, Memory: 8 GB). The calculation time was short with practical accuracy.

Possible flood event in Tone river system

We conducted possible flood disasters in the Tokyo metropolitan area using the models listed in Table 1. We generated a rainfall event with a 200-year return period from observed rainfall distribution during Typhoon Stella (Typhoon No. 5) in 1998. Accumulated rainfall was 135 mm/72 hours in the Tone catchment area, while that of the 200-year return period was 319 mm/72 hours. We multiplied the observed rainfall data by 2.3 times and assumed the return period of the new rainfall data was 200 years. We also assumed that a section of the levee close to gauging station B breached. We input the rainfall data and the levee failure scenario, and we obtained the simulation results of a 920-km^2 flooded area. The calculation time for simulating the 72 hour-event was 13 hours.

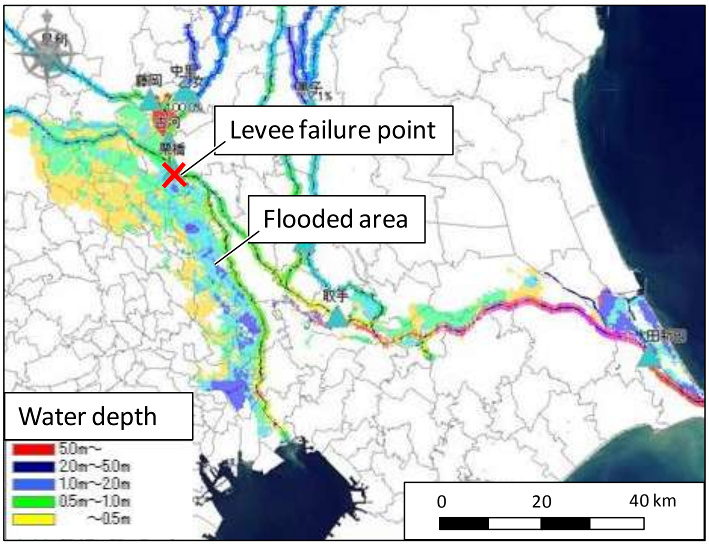

Figure 6. Flood area caused by heavy rainfall with 200-year return period and levee failure

4. CONCLUSIONS

1. We integrated a GIS and modeling environment and assessed the effects of the integration on simulating large-scale floods in metropolitan areas. We explained graphical user interfaces enabled by this integration and how this facilitates the preparation of modeling a large river system with many flood control facilities.
2. We discussed the Tone river system, which has the largest catchment area in Japan. Errors of simulated peak water levels in a past high water event (Typhoon Fitow, 2007) at ten gauging stations were less than or equal to 0.4 m. The calculation time of the simulation for simulating the 72 hour-event was 2 hours by using a computer manufactured in 2009. We also conducted a possible flood caused by levee failure and heavy rainfall with a return period of 200 years. Based on this simulation, 920 km^2 of the Tokyo metropolitan area was flooded. Calculation time was 13 hours.
3. Though the target was a large-scale flood, our integration method effectively facilitates modeling and enables fast calculation with practical accuracy on a conventional computer.

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