

A DISTRIBUTED FLOOD INUNDATION MODEL INTEGRATING WITH RAINFALL-RUNOFF PROCESSES USING GIS AND REMOTE SENSING DATA

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ABSTRACT:

Flood hazard is one of the most harmful disasters in the world, and it is significant to obtain information on flood characteristics for disaster mitigation as well as vulnerability assessment. This paper develops a distributed model for simulating flood inundation integrating with rainfall-runoff processes. The model is designed to apply the Shuttle Radar Topography Mission (SRTM) DEM data and some remote sensing data sets in the environment of GIS, which employs the simplified process representation capable of simulating flood inundation. In the model, it takes a one-dimensional diffusion wave representation for channel flow and a two-dimensional diffusion wave approximation of overland flow solved with the application of an explicit finite difference scheme. And the exchange of flows between river channel and overland surface is calculated through Manning's formula in response to the relative water surface elevation. Simulated results in the Maruyama River basin demonstrate an acceptable agreement with the flooded area observed. Hence the flood vulnerable area is able to be identified and delineated. This research is a fundamental step to assess flood hazard vulnerability.

1. INTRODUCTION

1.1 General Instructions

As the occurrence of flood event has become common in many parts of the world, flood events during previous years have raised public, political and scientific awareness of flood risk and flood prevention (Becker, 2003). In 2007, the frequency, distribution and causes of floods over the last thirty years has been analyzed and reported by the Dartmouth Flood Observatory, and a five-fold increase in the number of floods per year has been observed since the 1980s. Flooding threats are likely to increase given current climate change predictions, especially in terms of financial losses. Whilst much more people live in floodplain or low-lying areas, society becomes more exposed to flood events. Consequently strategies to cope with flood disasters, for example structural measures such as reservoirs and levee projects, and non-structural measures such as floodplain regulations, insurance, emergency preparedness etc. are taken. These countermeasures rely on flood prediction capabilities, and especially, the ability to delineate potential flood inundation areas is one of the most important requirements.

Geographers, first in collaboration with physical and applied scientists and then increasingly utilizing methodologies developed within the field, have made significant contributions in the research of disaster, risk, and vulnerability. Recently a shift in paradigms is observed from a technical oriented flood protection towards flood risk management, and the change in focusing from 'impacts-led' approach to 'vulnerability-led' approach and living with the risk are recognized (Adger, 2004). It is necessary and significant to study on regional vulnerability of flood hazard. To determine the regional vulnerability, the information about topography, hydrology, hydraulic or economy can be integrated in computational models.

During the past two centuries, scientists and engineers have sought to develop models to represent and predict the behaviour of water flow within canals, rivers and watershed (Singh, 2002). To date with the application of geographical information system (GIS) and remote sensing techniques to water resources management, more and more researchers are involved in developing a distributed hydrological model to simulate runoff and stream flow in watershed. On the other hand, numerical hydraulic models of overland flow provide the capability to simulate flooding based on a scenario discharge, the estimation of reach scale flood inundation has been studied (Horritt, 2001; Horritt, 2002), especially numerical inundation hydrodynamic model in urban area due to heavy rainfall has been developed (Kawaike, 2000; Toda, 2005).

However, it was pointed out that floodplain management is being seen increasingly in a catchment wide context (Van Roon, 2001). Therefore it is significant to develop an integrated model applicable to any catchments for flood vulnerability assessment. In this study, it proposes a simplified distributed flood inundation simulation model integrating with rainfall runoff processes to obtain analytical result of vulnerability to flood hazard in the context of catchment.

Topographic data are crucial for flood inundation modelling, thus much interest has focused on the adoption of highly accurate topographic data such as airborne laser altimetry data or LiDAR to parameterize flood inundation models (Horritt, 2001). However, the data availability is not always feasible because of given time and budget constraints. The first near-global high-resolution digital elevation model of the Earth has been released following the successful Shuttle Radar Topography Mission (SRTM) in the year 2000, which is especially valuable in the Earth sciences and has a wide range of application fields. In this study the freely downloaded SRTM

DEM with the resolution of 90 meters as a source of terrain data for flood modelling is focused.

The objectives of the present study are: (a) to develop a distributed flood inundation model integrating with rainfall-runoff processes for large areas; and (b) to take advantage of globally available data to simulate flood inundation for further study of flood hazard vulnerability assessment at any catchments.

According to the simulation result, flood characteristics were well captured and the flood vulnerable area was identified and delineated efficiently. This paper is organized as follows. In section 2 we give the methodology. Section 3 addresses the description of the study area. Section 4 is the application of distributed model. Last section is some concluding remarks.

2. METHODOLOGY

2.1 Model descriptions

Spatiotemporal information of flood events is of the utmost importance for flood disaster mitigation as well as for flood vulnerability assessment. A flood inundation simulation model integrating with rainfall-runoff processes is developed in this study, which is based on simplified process representation to obtain simulation of flood water depth and hence inundation extent. The model architecture is described below.

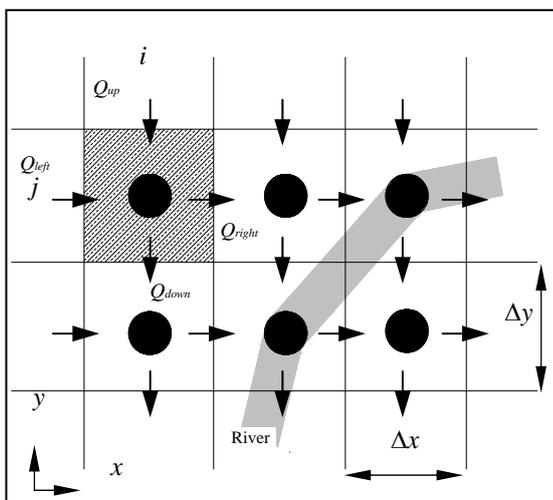


Figure 1. Scheme of 2-D overland flood routing and channel routing.

Overland flow which originates from precipitation or saturation excess on the soil, flows into the river channel. When the bankful flow depth is reached in the river channel, water flows out of the river channel into adjacent surface areas (Figure 1). Therefore these surface areas act either as temporary tanks for flood water or additional routes for flow conveyance. In this process, the water surface elevation for river channel is calculated using a one dimensional channel flow model. Overland surface flow routing over the whole watershed is simulated by a 2-dimensional model, which is to treat each grid as a storage cell, and the change in cell volume over time is equal to the rainfall excess and fluxes into or out of it. Whilst at the interface between river channel and overland surface area, the exchange of flow is simply simulated in response to the

relative water surface elevation, i.e., surface flow can be either away from river or into river (Bates, 2000; Toda, 2005) (Figure 2).

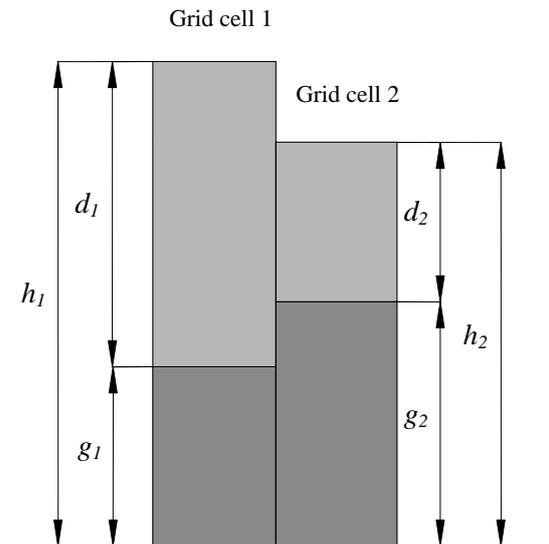


Figure 2. Flow between grid cell 1 and 2 (d , depth of water in the cell; g , ground elevation; and h , water surface elevation in the cell).

The processes of overland flow and channel flow can be modelled using approximations of the Saint Venant equations (Singh, 1996). Gonwa, Kavvas and others have demonstrated that the diffusion wave approximation to the full Saint Venant equations is appropriate for many cases of practical interest (Gonwa, 1986). In some simulation models based on kinematic wave approximation, flow directions for the stream network are generated from DEM data. However, it can not deal with the backwater situations. Therefore diffusive wave approximations are employed as the governing equations for both overland and river channel flows.

2.2 Governing equations

Hydrologic and hydraulic modelling requires a clear understanding the hydrologic cycle at catchment scale. The model proposed here is based on raster data structures, and grid cells are adopted to describe distributed watershed characteristics using such as elevation, land use, soil type, etc., where flood inundation integrating with rainfall-runoff processes are simulated for every grid cell.

The rainfall excess (R_e) over the cells is assumed to equal to the sum of the amounts of precipitation to the ground (R_g), interception (v_i), and infiltration (v_f). For the sake of simplicity, being an event based flood runoff and inundation model, evapotranspiration is not taken into consideration. Therefore the rainfall excess is calculated by Eq. (1).

$$R_e = R_g - v_i - v_f \quad (1)$$

In this research, during the simulation, if the rainfall intensity is less than the intensity of interception, the rainfall rate is set to zero and the remainder of the interception is removed from the rainfall in the following time increments until the interception depth has been satisfied. The infiltration is obtained from the one-layer Green-Ampt infiltration model, assuming the soils are

homogeneous, deep, and well-drained within each grid cell (Raws, 1983; Maidment, 1993).

Overland flow is governed by the continuity and momentum equations: Eq. (2) and Eq. (3) (Horritt, 2001; Toda, 2005). To solve the overland flow equations, explicit finite difference method is selected. In order to solve the continuity equation relating flow into or out of a grid cell and its change in volume, momentum equation for each direction is calculated according to Manning's formula:

$$\frac{dh^{i,j}}{dt} = \frac{Q_{up} + Q_{down} + Q_{left} + Q_{right} + R_e}{\Delta x \Delta y} \quad (2)$$

$$Q_x^{i,j} = \pm \frac{h_{flow}^{5/3}}{n} \left| \frac{h^{i-1,j} - h^{i,j}}{\Delta x} \right|^{1/2} \Delta y \quad (3)$$

where $h^{i,j}$ is the water free surface height at the grid cell (i, j) ; t is time; Δx and Δy are grid cell sizes; n is the Manning's friction coefficient; Q_x and Q_y are the volumetric flow rates between grid cells in x and y directions, whose sign depends on the flow direction. Q_y is defined analogously to Eq. (3); Q_{up} , Q_{down} , Q_{left} , and Q_{right} are the flow rates (either positive or negative) from the up, down, left and right adjacent cells, respectively, which can be represented by Q_x or Q_y accordingly (Figure 1). The flow depth, h_{flow} , represents the depth through which water can flow between two cells.

To obtain water which flows into or out of river channel at the interface between river channel and floodplain area or low-lying area, the exchange of flow is calculated using Manning's formula (Eq. (3)), as overland flow calculation.

In this study, the location of channel network is predetermined by using ArcGIS software, and a river channel may run not only in the x or y direction but also along the diagonal directions. Under this setting, channel flow is also represented by the continuity and momentum equations (Eq. (4) and Eq. (5)).

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (4)$$

$$S_0 - \frac{n^2 P^{4/3} Q^2}{A^{10/3}} - \left[\frac{\partial h}{\partial x} \right] = 0 \quad (5)$$

where x is distance along the longitudinal axis; A is cross-sectional area; Q is discharge; q is lateral flow into or out of river channel; P is wetted perimeter of channel flow; s_0 is bed slope.

2.3 Model development approach

The primary objective of this research is to develop an integrated flood inundation simulation model to predict and analyse flood hazard. Here a loose coupling method of program development is selected. In such case, GIS and flood inundation simulation model remain separate, but loosely linked through data input and output operation (Figure 3).

The model program is developed according to the methodology mentioned in the above under the environment of Microsoft Visual C++ and Windows operating system, in which the hydrologic processes including precipitation, interception and infiltration are considered.

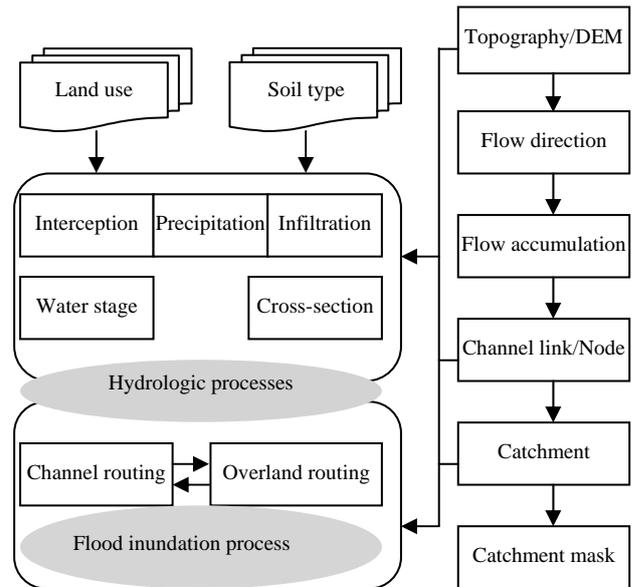


Figure 3. The model development scheme.

3. DESCRIPTION OF THE STUDY AREA

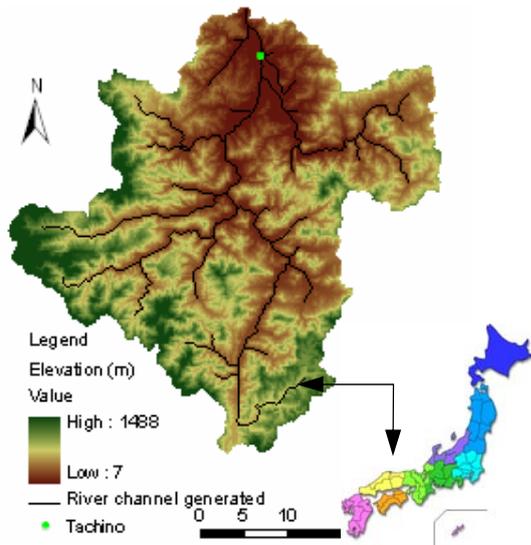
The integrated model described in the above section is applied to the Maruyama River basin, which is located in the Hyogo Prefecture, Japan (Figure 4). Within the mountain boundary there are hills and lower lands. The Maruyama River (Class A river system in Japan) flows from its source of Maruyama mountain, to Tajima district and then runs northward through the Toyooka basin to the Sea of Japan, whose mainstream length is 68 km, and the total length of its tributary is 638 km. The area of the Maruyama River catchment is 1,330 km² with the population of 152,000, where the mountain area accounts for 86% and about 30% residents inhabit in the downstream floodplain area. From the river outlet to the upstream 16 km, the river bed slope is very flat (1/10,000). Upstream of this part, the bed slope is 1/500. The elevation ranges from 7 m to 1488 m. The mean annual precipitation is about 2000 mm. There are some tributary channels such as the Izushi river, and the Inaba river. The special topographic conditions result in this area being vulnerable to flooding, even though levee breaching does not occur (Takara, 2005).

From 19th to 21st October 2004, Typhoon No. 23 hit the Japanese islands, which brought precipitation as much as 278 mm in the Toyooka area over a two-day period, the heavy amount of water flowed into the mainstream of Maruyama River, which caused severe flooding and levee breaching (Takara, 2005; Kinki Regional Development Bureau website, 2007).

4. MODEL APPLICATION TO THE MARUYAMA RIVER BASIN

4.1 Data preparation

For the estimation, some general information about local situation must be available. Generally four kinds of data are required: (a) topographic data or DEMs to construct the model grid; (b) bulk flow data to provide model inflow and outflow boundary conditions; (c) effective friction parameter for each grid cell; and (d) some validation data. In the following, the required data preparations are introduced.



(The map of Japan in the right corner is taken from <http://www.japanfs.org/en/japan/index.html>.)

Figure 4. The study area with DEM and river channel generated.

4.1.1 DEM data

For both the calculation of overland flow or channel flow and the estimation of the inundated areas, elevation information in the model area is required. In order to simulate the large area hydrologic process, DEM data is downloaded from USGS (U.S. Geological Survey) website, its spatial resolution is around 90 meters, and in this study it has been extracted, projected and re-sampled with the resolution of 200 meters, in which the numbers of row and column are 259 and 250 respectively (Figure 4). SRTM DEMs are based on interferometry, which involves the reception of a backscattered radar signal by two antennae. The signals include radar speckle, or random noise, which degrades relative vertical accuracy particularly on floodplains (Gorokhovich, 2006). Hence, data filtering to remove data speckle is adopted to enhance the quality of SRTM.

4.1.2 River channel generation and channel parameterization

River channel (Figure 4) is derived from DEM data after pit removal in ArcGIS software environment. The river channel is discretized to route on grid cells, and utilized combining with the catchment DEM. For model parameterization, channel cross-sectional geometry is specified as trapezoidal. The required parameters at each grid cell along the river channel are bank height, channel width, and side slope, which can be specified at each grid. The channel parameters are supplied in terms of documents about the Maruyama River basin. The channel width ranges from 20 m to 150 m, which is extracted under Google Earth environment (Table 1).

4.1.3 Auxiliary data

In order to apply the proposed model to any catchments, land cover and land use classification data is downloaded from GLCF (Global Land Cover Facility) website, whose resolution is 1 km. After re-projection, re-sampling and extraction, these data are overlaid to the watershed grid system. Suppose that it is necessary to get higher resolution data, MODIS satellite data

can be employed. Precipitation (Figure 5) is collected from field measurements. There are eight rainfall stations distributed in the study area (Figure 6). The inverse distance weighted method is used to interpolate precipitation for each grid cell. Other input parameters such as Manning's roughness coefficient are provided from the published literature (Chow, 1988; Maidment, 1993). The roughness values for the overland surface grid cells and interception storage capacity are specified based on land use classification (Table 2). Soil type is extracted from the soil map of Japan (1:1,000,000).

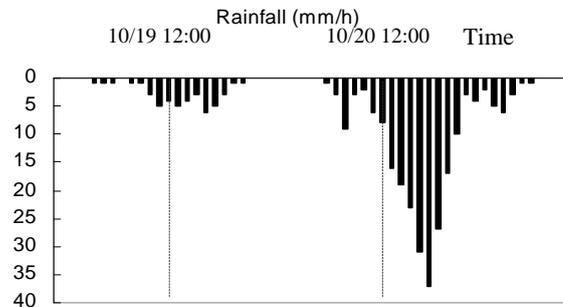


Figure 5. Rainfall in the Maruyama River Basin.

Channel number	Bank height (m)	Side slope (H:V)	Width (m)	Initial water depth (m)	Manning's coefficient
1	4	0.10 (Trapezoid)	30	0.5	0.03
2	5	0.00 (Rectangle)	48	0.6	0.03
3	8	0.00 (Rectangle)	150	1.0	0.03
4	3	0.25 (Trapezoid)	25	0.5	0.03

Table 1. Example of river channel properties (Note: Channel number is the number of generated river channel segment)

Land use	Evergreen needleleaf forest	Evergreen broadleaf forest	Deciduous needleleaf forest	Deciduous broadleaf forest
Manning's coefficient	0.040	0.040	0.040	0.040
Interception (mm)	3	3	3	3
Land use	Closed shrublands	Open shrublands	Woody savannas	Savannas
Manning's coefficient	0.035	0.035	0.030	0.030
Interception (mm)	3	1	1.5	1.5
Land use	Mixed forests	Croplands		
Manning's coefficient	0.040	0.030		
Interception (mm)	3	1.5		

Table 2. Manning's roughness coefficients and interception of different land use classification

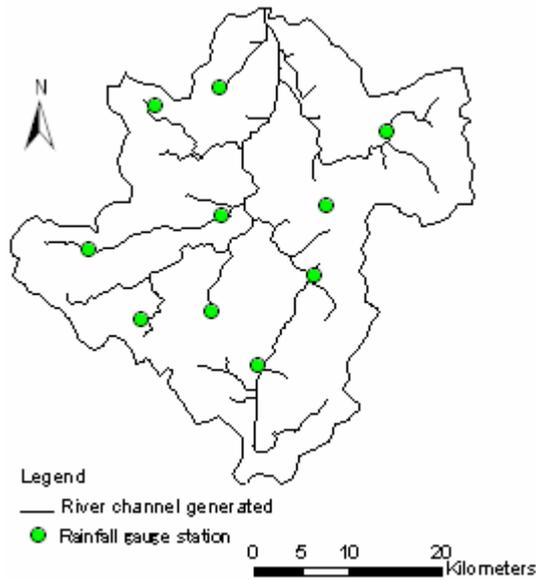


Figure 6. The rainfall gauge stations in the Maruyama Basin.

4.2 Simulation result analysis

The Typhoon 23 in the year 2004 brought a heavy rainfall in the Maruyama River basin, which resulted in large flood inundation at Toyooka city area. In this research, the integrated model is applied to study this flooding case. Although the model simulation results are composed of flood discharge and distributed flood inundation depth, here the comparison of the flood inundation extent is emphasized, because flood extent data has proved to be a valuable tool for calibrating and validating numerical hydraulic models (Bates, 2000). In Figure 7, the final spatial distribution of flood inundation is shown, which indicates the model can simulate the flooding process and identify the flood vulnerable area.

The simulated flood extent inside of blue broken line at Figure 7, magnified as Figure 8, is similar to the inundation extent observed (Figure 9), in which the flood inundation area observed is about 41 km², and the simulated inundation area is 42.49 km². According to the overlay analysis of simulated extent and observed extent, around 30.22 km² inside of the observed inundation area is located in the simulated inundation extent, which shows the consistency ratio is about 75%.

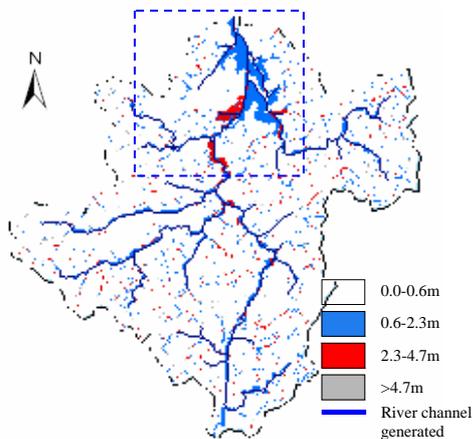


Figure 7. The simulated flood spatial distribution.

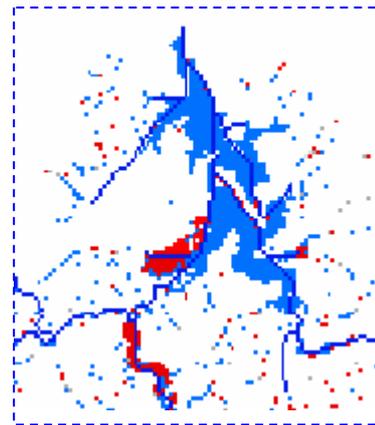


Figure 8. The zoomed image inside of the blue broken line in figure 7.

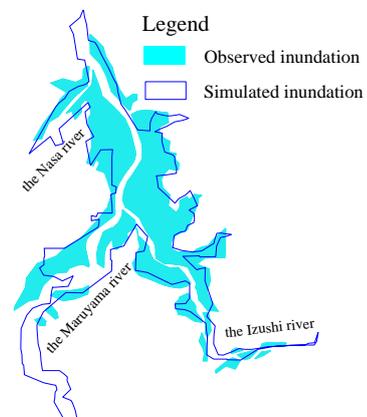


Figure 9. The comparison of flood inundation area.

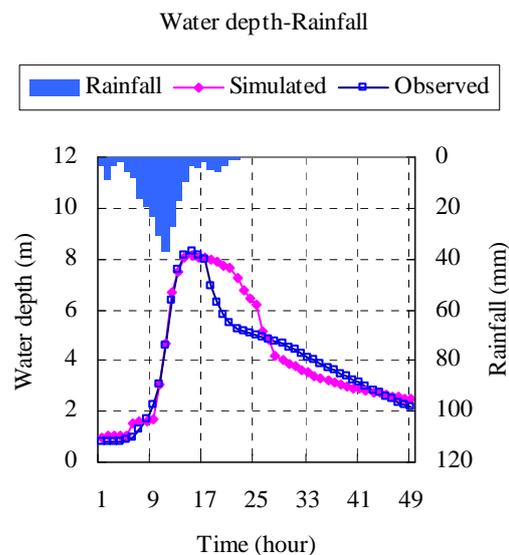


Figure 10. Water depth comparison (Site: Tachino station).

In the simulation the river channel is generated from DEM, which is a little different from the actual river, therefore it has an effect on the spatial distribution of flood inundation, and it is not easy to compare the spatial distribution of flood inundation

directly. However, based on the analysis of spatial distribution of flood inundation at Toyooka city area, it shows an acceptable agreement. Further analyses about the accuracy and uncertainty of flood inundation simulation can be studied when more detail data such as river channel and flood extent observation are gathered.

The comparison of river water depth at the Tachino station after 7:00am on October 20th, 2004 is shown in Figure 10. The peak of water depth and its change are well reproduced, which reflect this model is effective. The descent of simulated water depth is not very rapid, which is because the model does not include levee breaching at present, but this is able to be incorporated into model for scenario analysis.

5. CONCLUDING REMARKS

In this study, the physically based distributed flood inundation simulation model coupled with hydrologic processes for catchment scale context is developed with the application of globally available data. The model calibration results demonstrate that the overall model performance is acceptable, which provides a feasible modelling tool to simulate the flood inundation and is of significance to flood vulnerability assessment, especially focusing on overflow flood. All the parameters employed in the model are physically based, and almost model input data can be acquired from open source data, therefore it is possible to apply the model for flood hazard management in data poor environment.

However, the precision of model simulation not only depends on DEM accuracy, but also relies on hydrologic and hydraulic model structure. At present, the hydrologic model only takes surface water flow into consideration and the hydraulic process is simplified. In order to improve the model applicability for various hydrologic environments, the subsurface flow and other detail process models need to be coupled in the further study.

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