Comprehensive Flood Control Measures in Tokyo and Advanced GIS-based Urban Catchment Runoff Model

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ABSTRACT: In order to alleviate and prevent increasing flood damages due to urbanization, the comprehensive flood control measures including structural and non-structural ones are introduced in Tokyo from the viewpoints of not only the rivers but their basins. Many overflow detention facilities and artificial underground flood retarding reservoirs have also been constructed in Tokyo. To evaluate these measures and predict the flood discharge and inundated area, the advanced GIS-based urban catchment runoff prediction model is presented. This model is a physically based distributed model incorporating recent advancement of GIS delineation, which precisely describes spatial characteristics of an urban catchment. By this GIS delineation, flow paths can be traced with a very high level of detail. The flow calculations in the different modules are simulated by one-dimensional hydrodynamic models incorporating the interaction between the sewage system, the river system, the streets, and the areas flooded with stagnant water based on established concepts and equations. The model is set up for an urban subcatchment of the Kanda River (Tokyo, Japan) and applied to simulate the runoff response to an actual storm event. It is found that the model can simulate both the physical rainfall-runoff process as well as inundation in the basin in a satisfactory way.

1 INTRODUCTION

Urbanization has been a universal phenomenon since the later half of the 20th century. This phenomenon is especially dominant in the megacities like Tokyo. With the progress of urbanization in the form of high density housing-land development, the water retention capacity of the land has declined because of the increased amount of impervious surface areas and the extension of sewage system. As a result, the flood reach hour is significantly shortened and the flood peak discharge is drastically increased in urban catchments. With increased property values of buildings and other structures, potential damage from prolonged flooding can easily extended in the millions of dollars. To alleviate and prevent increasing flood damages as a result of urbanization, recent high incidence of local torrential rains and the increase in underground spaces, the comprehensive flood control measures including structural and non-structural ones are introduced in Tokyo. Many overflow detention facilities and artificial underground flood retarding reservoirs have also been constructed in Tokyo.

Urban catchments are formed as very complicated artificial structures, such as buildings, houses, roads, parking lots, parks, waterways, underground sewer system and so on. So far, mainly grid based distributed models are used as rainfall-runoff models not only in mountainous and rural catchments, but also in urban catchments due to their simplicity and the limitation of available information of the catchments. Grid based models, however, are not appropriate for urban catchment modeling, because those models greatly average the land use property into each grid cell ignoring individual land structure property of the urban catchment.

Recently, with the progress of GIS (Geographical Information System) technology and the development of the related geographical data, digital information on road network, grid based land use, sewer and drainage system has been rather easily available. GIS information on geographical feature, such as individual building, house, parking lot, park etc., for rainfall runoff modeling has also been prepared in the large cities. Physically based distributed flood runoff model using geographical feature data can exactly trace the rainfall runoff process in urban catchment. The physically based distributed model presented here takes advantage of GIS information of geographical feature data to take precisely into account of impervious and pervious areas as individual structure or segment of the urban catchment.

The advanced GIS-based urban catchment runoff model is simulated by one-dimensional hyrodynamic modeling incorporating the interaction between the sewage system with manholes, the river system, the streets, and the areas flooded with stagnant water. The model uses two types analytical models: hydrological models which simulates surface runoff from rainfall, and hydraulic models which describe river flow, sewer pipe flow, and the flow of storage water on the surface of streets and residential blocks. The computation of the surface runoff from rainfall is carried out by a standard kinematic wave model. A surface runoff hydrograph is computed for each single area. Runoff hydrographs from each single area are then used as input for the hydrodynamic model, simulating flows in the pipe and street systems. The model is set up for a flood-prone urban subcatchment of the Kanda River (Tokyo, Japan) and applied to simulate the runoff response to an actual storm event.

2 COMPREHENSIVE FLOOD CONTROL MEASURES IN TOKYO

The conventional flood control measures have improved rivers mainly by expanding their channel width to prevent frequent flood damage. However the urban development of the surrounding area of Tokyo increased the outflow into rivers, shortened the flood reach hours, and reduced the safety at rivers from flooding. With this as a backdrop, the comprehensive flood control measures intend to alleviate and prevent flood damages from both the viewpoints of rivers and their basins. Figure 1 shows a conceptual view of the overall flood control measure systems. Rainfall are absorbed not only by channels but the by entire basin, while the flooding can be cut by means of regulation reservoirs, pools, etc. And temporarily stored water allows rainwater to permeate the soil and replenish underground water.

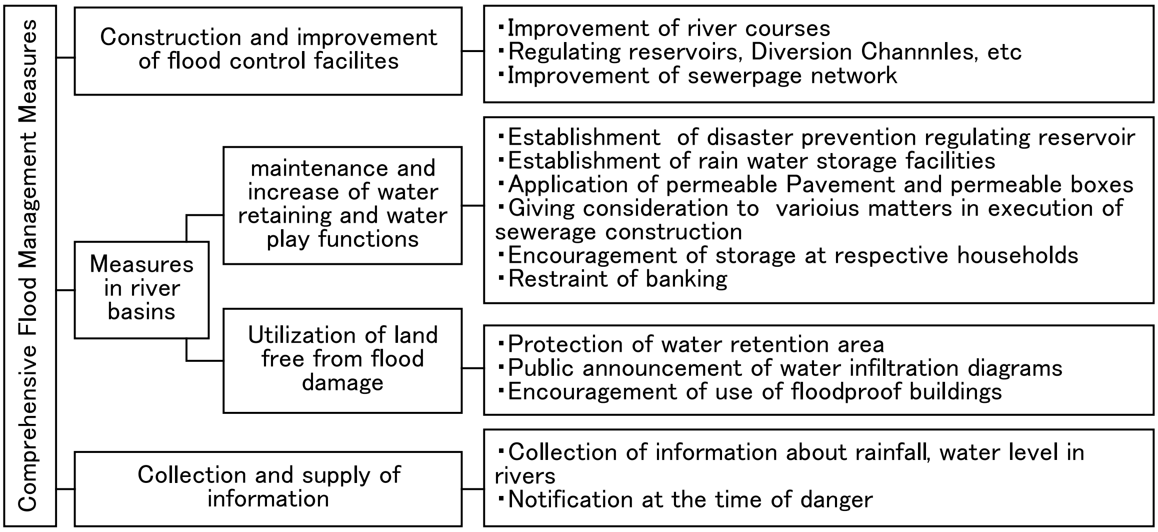


Figure 1. Total systems of comprehensive flood control measures.

As one of the main hard flood control measures Tokyo Metropolitan Government Bureau of Construction (2007a) has constructed the underground flood retarding reservoir with the capacity of 540 thousand m^3 under the Loop Road No. 7. The reservoir was constructed as 4.5 km long tunnel with inside diameter of 12.5 m, which is in the future planned as the part of the larger underground river (or floodway) project.

The government bureau has also been developing hydrological data acquisition system by telemetry rainfall information systems, for accurate and speedy collection of rainfall, water level and other hydrologic data through their own networks (Tokyo Metropolitan Government Bureau of Construction, 2007b). There are 138 rainfall gauges, 150 water level gauges, 31 sea level gauges and 21 reservoir gauges all over Tokyo. Figure 2 shows an outline of Tokyo and distribution of rainfall and water level gauges. The stations are mostly remote controlled and the information about the precipitation and flood can be collected and transferred automatically every one minute.

3 ADVANCED GIS-BASED URBAN CATCHMENT RUNOFF MODEL

3.1 Conceptual Design of the Model

In order to evaluate the comprehensive flood control measures in urban catchment as one of the main purposes,

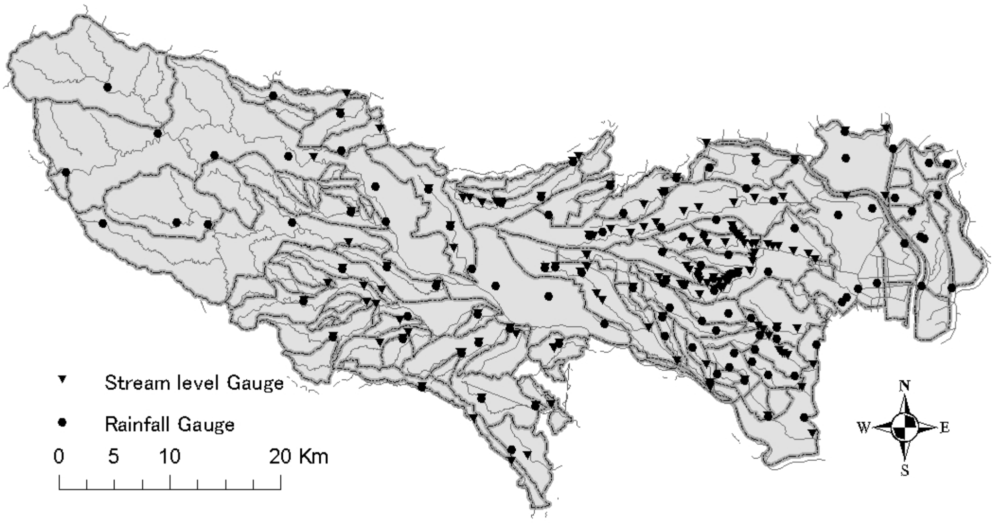


Figure 2. Rainfall and stream level observation gauges by Tokyo Disaster Information Sytem.

the authors propose an advanced GIS-based urban catchment runoff model (Amaguchi, 2005; Amaguchi *et al.*, 2007). The model is a physically based distributed model incorporating recent advancement of GIS delineation, which precisely describes spatial characteristics of an urban catchment. By this GIS delineation, flow paths can be traced with a very high level of detail. The flow calculations in the different modules are simulated by one-dimensional hydrodynamic models incorporating the interaction between the sewage system, the river system, the streets, and the areas flooded with stagnant water based on established concepts and equations.

Figure 3 shows the modeling approach for urban flooding based on advanced GIS delineation. The hydrological model calculates direst runoff component from rainfall, which is combined with various hydraulic models of surface flow model, pipe flow model and river flow model. They describe water flows of street surfaces, residential blocks, sewer pipes and rivers. The hydrodynamic flows calculated by the above three major hydraulic models are based on the solution of Saint-Venant equations.

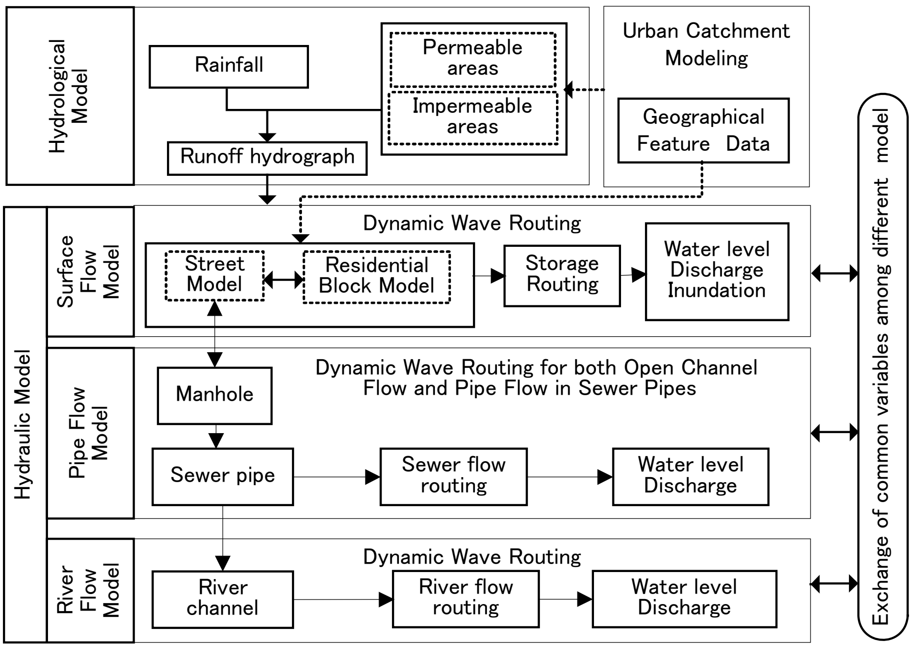


Figure 3. Interaction among various hydrologic and hydraulic models.

The rainfall is given to each minute element of land use components inside the residential block and to each divided segment of roads and rivers, which are extracted from advanced GIS delineation data. In urbanized catchments, the main contribution of direct runoff stems from surface flow from impervious elements inside the residential blocks and road elements. The direct runoff is also caused by overflow from pervious elements inside the residence blocks, which is calculated as excess water quantity over its infiltration capacity of the pervious element. The computation of the runoff volume from each minute element of land use components and each divided segment of roads is carried out using a standard surface runoff model such as kinematic wave model. The calculated runoff volumes (or hydrographs) of each element and segment are then used as the input for hydraulic models in Fig. 3.

The direct runoff is drained to sewer system through manholes of the road elements. The information on the pervious and impervious properties is extracted from the characteristic of land use elements, such as building, house, road, parking lot, park, play ground, wood area, cultivated field, and so on. The underground sewer system is expressed by the network of nodes and conduits. The SLOT model, a practical sewer pipe simulation model by Watanabe *et al*. (1990) is used to analyze the transition between open-channel and surcharge flows in sewer pipe networks.

Inundation flow characteristics are complicated in an urban catchment due to such as blocking by buildings. In this paper, to treat inundation flow between residential block and road (or river), the concept of "street network model" is used (Inoue et al., 1998). In the model, the street network consists of links of streets, nodes of cross points and residential blocks.

All of the hydrologic and hydraulic models are built up and coded by authors using FORTRAN computer language.

3.2 Urban Catchment Modeling with Advanced GIS delineation

In order to express faithfully the urban storm process illustrated in Fig. 3, we make use of advanced GIS data to exactly delineate the surface objects and surface land use elements. Figure 4 illustrates the urban catchment modeling with advanced GIS delineation. As shown in the figure, from the land surface of the whole catchment we can extract individual buildings and houses, residential blocks and rivers using already existing basic GIS data. The remaining parts after extracted by residential blocks and rivers automatically indicate part of roads in

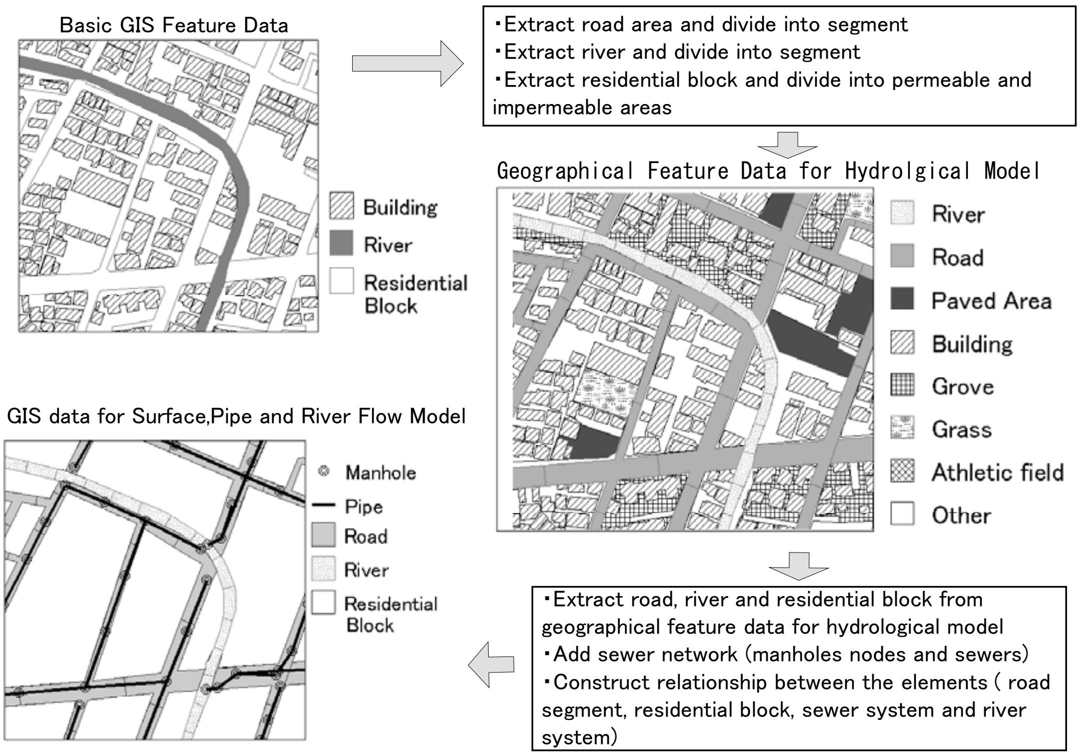


Figure 4. Urban catchment modeling with advanced GIS delineation.

the catchment. The next step is to extract land use components inside the residential blocks manually using a topographic map of scale 1/2500. In this case, those are the elements of paved area, grove, grass field, athletic field etc. except for building elements which are already extracted. Then the road and river components are divided into small segments. The ground heights of all elements are assigned using 5 m DEM produced by the Japan Geographical Survey Institute. Finally, sewer pipe network data with manhole information are added in the GIS system, which build up the advanced GIS data for the rainfall runoff calculation using the above-mentioned hydrologic and hydraulic models. The GIS software ArcMap is used in this urban catchment modeling process.

4. CASE STUDY

The study area selected for the model application is a small urban catchment, named the Ekota river catchment in the Kanda river basin, Tokyo, Japan as shown in Fig. 5. The selected lower Ekota sub-catchment area is about 1.1 km^2 and the river length is about 1 km. Utilizing the above-mentioned advanced GIS delineation technique, all of the land surface elements in the study area, i.e. minute elements of land use components inside the residential block, divided segments of roads and rivers, are precisely extracted as shown in the left figure of Fig. 6. The total number of all land surface elements amounts to 6,922. More than 60% of the basin is occupied by impervious land use elements. The sewer pipe network data were inputted by hand using GIS software from paper-based sewer network maps from the Bureau of Sewerage after scanning (right figure of Fig.6). The properties of pipes and manholes, such as diameter, gradient, height, were also traced manually.

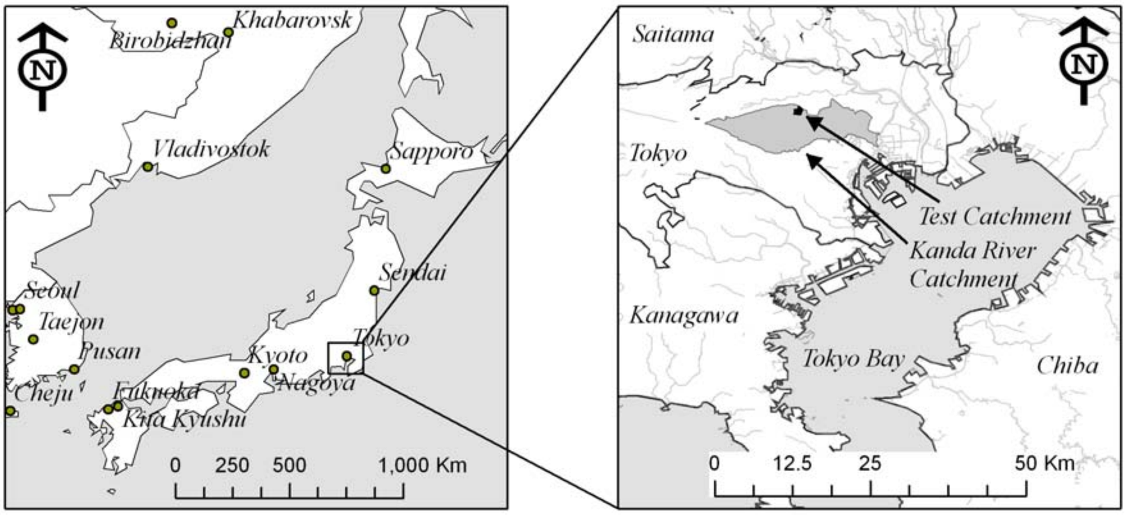


Figure 5. Study area (lower Ekota sub-catchment).

Figure 7 shows an example of rainfall runoff analysis by the proposed model for the storm event on October 20, 2004 caused by the Typhoon no.23. There is one rain gauge in the study area, and the rainfall data were recorded at 1-minite intervals by Tokyo Metropolitan Government. On the other hand, no river water level gauge was installed in the sub-catchment except for its upper boundary at that time. However, we ourselves went to the river soon after the storm event started and dared to conduct the field observation of water level on site by reading the staff gauge every 5 minutes. We were luckily able to obtain the data from the second peak of the hydrograph till its decreasing part (Fig. 7). The observed water level data are also converted into the discharge using the river properties information. As shown in Fig. 7, the calculated water levels (and discharges) are quite well fitted to the observed ones, although the model parameters, which are necessary for the hydrologic and hydraulic models, are just set as their standard values. In this storm event, no inundation occurred.

Figure 8 shows an example of simulation results of flood inundation for the storm event on August 21, 1999. Although there was no real record of spatial distribution of actual inundation available, based on the hearing survey with local people, it was found that the simulated inundation pattern (Fig. 8) was close to the actual inundation situation. The developed model can also express the inundation process in a suitable way.

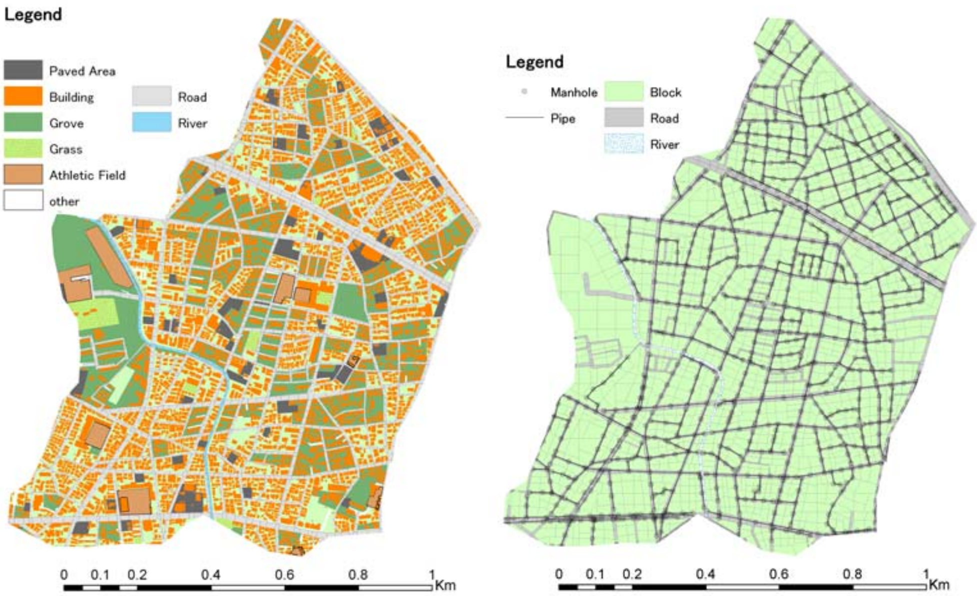
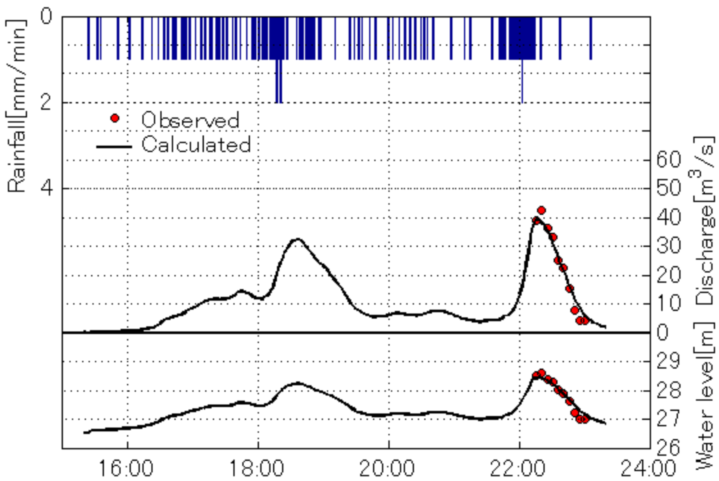


Figure 6. Study area delineated by advanced GIS data technique.



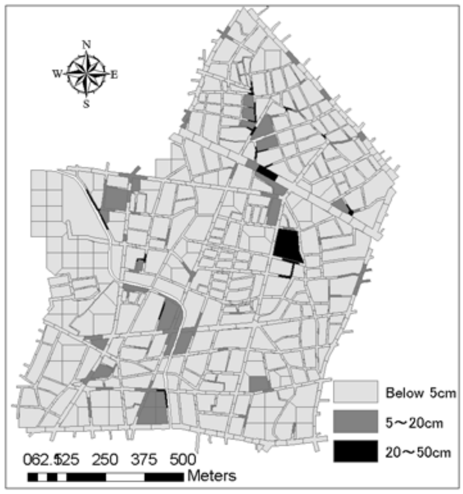


Figure 7. Rainfall runoff result by the proposed model. **Figure 8.** Estimated maximum depth of inundation.

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