STORM RUNOFF ANALYSIS IN THE UPPER KANDA CATCHMENT BY THE TOKYO STORM RUNOFF MODEL

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The recent advances in GIS technology as well as data availability open up new possibilities concerning urban storm runoff modeling. In this paper, a vector-based distributed storm event runoff model - the Tokyo Storm Runoff (TSR) model - is applied for urban runoff analysis. The set-up of this model is based on urban landscape GIS delineation that faithfully describes the complicated urban land use features in detail. The model was set up and evaluated for the upper Kanda catchment in Tokyo Metropolis, Japan. The runoff response to actual storm event and hypothetical rainfall events were simulated. 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.

Keywords: Vector-based catchment delineation; Storm event runoff model; Tokyo Storm Runoff model; Urban hydrology; Urban landscape GIS delineation

Introduction

The urban environment is characterized by its abundance of impervious surfaces (roofs, roads, parking lots etc.), from which runoff is rapidly generated as overland flow. Under normal conditions, this flow enters the sewage system to finally be drained to a receiving watercourse, typically a river or an open channel. If the generated runoff exceeds the storage capacity of the sewage system, surface flooding is caused by excess water outflowing from manholes and inlets. The flooding may be exacerbated by a simultaneous overflow of the receiving watercourse.

There is thus both a static and a dynamic aspect of the need for modeling of urban storm runoff and flooding. The static aspect represents the need to evaluate the properties and risks of flooding in a city in its present state, e.g. to produce flood risk maps as required by legislation. The dynamic aspect, on the other hand, reflects the fact that urban environments as well as its climatological characteristics are constantly changing and the consequential need to evaluate flooding response to these changes.

Modeling of flooding in urban catchments is generally based on the concept of “dual drainage”, i.e. linked modeling of the subsurface flow in the sewer network and the overland surface flow, respectively. The concept dates back over 20 years and early modeling attempts often included modification and/or combination of existing runoff models such as SWMM, EXTRAN and HEC to handle the different flow types (Smith 2006). A difficulty, however, concerned the huge efforts required to gather sufficiently detailed and reliable data on properties of both the sewer system and of the objects that govern the overland flow paths. The situation improved greatly in the 1990s, when the use of GIS data became widespread within the field of urban runoff modeling. With the objective of storm drainage analysis, Djokic and Maidment (1991) used GIS to describe the urban environment in terms of three basic elements: inlets, drainage network and surface terrain.

Recent model developments have undoubtedly led to a significant advancement of our understanding of the urban flooding process and our capability to simulate it with high accuracy. In the model approaches developed to date, however, the spatial characteristics of an urban catchment must be specified in a regular grid. Different types of raster (or mesh) have been used, from square or rectangular to somewhat more complicated shapes, but they all substantially limit the possibility to accurately describe the often highly irregular structure of the urban environment and the associated complex flow paths. We believe further progress is possible, in particular by combining an integrated modeling approach with a more elaborate use of GIS data, to faithfully reproduce the overland part of the integrated flow system. Especially to accurately estimate the combined effect of local but widely applied flood control measures (e.g. storage tanks and porous asphalt), a very high level of detail is required.

In this paper, a vector-based distributed storm event runoff model - the Tokyo Storm Runoff (TSR) model - is applied for urban runoff analysis. The modeling approach has been developed during recent years (Amaguchi et al., 2012) and is here presented including a case study.

The Tokyo Storm Runoff (TSR) Model

The hydrologic characteristic of an urban surface depends on its land use. The types of surfaces present ranges from the relatively impervious character of streets, parking lots and roofs, to the more pervious character of gardens, bare soil and parks. The geometric composition of these different types of surfaces that forms a block is usually complicated. This complicated and inhomogeneous nature of urban catchments makes it very difficult to model the runoff process with accuracy. However, by the use of what will be denoted “urban landscape GIS delineation”, which is described in detail below, the complex configuration of urban catchments can be faithfully reproduced in a runoff model. The model is thus designed to be a tool which makes it possible to simulate the flooding process in an urban catchment in a comprehensive, detailed and accurate way.

Figure 1(a) shows a schematic of the rainfall-runoff process as represented in the TSR model. When rainfall begins, water falling on a land use element inside a block or a road forms pools, where water falling on a river adds to the river discharge. Rainfall excess from blocks flows out directly or indirectly through different types of surfaces and finally out into the nearest road. When a manhole exists inside the road, water flows through it to the rainwater sewer pipe conduit. When no manhole exists, water flows down the road to an adjacent road element. In a manhole, the water level is obtained considering the inflow from the road together with the upstream inflow from connected pipe conduits. In a pipe conduit, the water flow is obtained considering the water levels in the manholes located upstream and downstream, respectively. When the water level in a manhole exceeds ground level, water flows out and inundates the associated road. The inundated water either flows to adjacent road elements until a manhole that has not reached full inflow capacity is found. It may also flow into and flood a block, if the water level in the road is higher than that in the block. The water in the sewer pipe conduits eventually reaches the river channel, which finally drains in the catchment outlet. Infiltrated water from pervious land use elements inside blocks finally drains out into the river as long-term groundwater runoff, which is however at present not considered in the TSR model.

Figure 1(b) shows an example of a detailed map of an urban catchment obtained by urban landscape GIS delineation. An urban watershed is split into homogeneous elements such as roads, rivers and different land use components. Surface is classified into pervious area and impervious area. Rivers, roads, paved area and buildings are included in the impervious area. Pervious areas comprise grove, grass, playgrounds

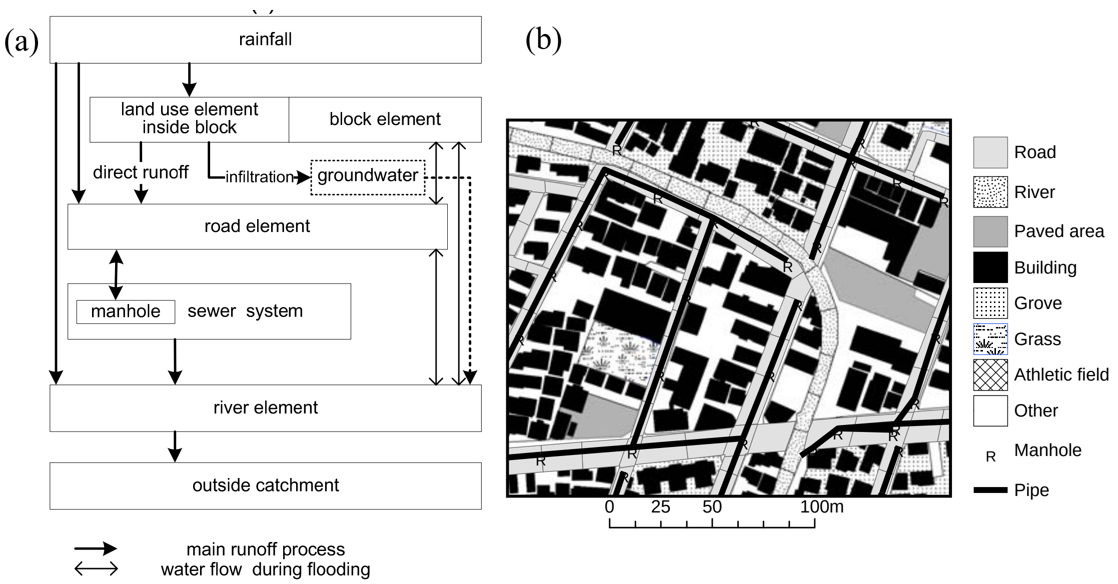

Figure 1: Schematic of the rainfall-runoff process (a) and Map representing the different spatial elements considered in urban landscape GIS delineation (b)

and others. In addition, urban landscape GIS delineation data also contains the sewer network system component that consists of pipe and manhole elements. For the runoff modeling, roads and rivers have to be divided into elements. Inside residential blocks, detailed land use information has to be added. This may include manual processing, in which map-based information is transferred to GIS format by appropriate GIS software.

Case Study

The study area selected for the model application is a urban catchment, which is located in the Kanda River basin Tokyo Metropolis, Japan, as shown in Figure 2a. The study catchment will be termed “upper Kanda catchment” and Figure 2b shows this catchment in some detail. The boundary of the study catchment is specified based on two conditions, the topography and the extension of the sewer pipe network. The upper Kanda catchment area is ~11 km² and the length of river inside it is ~10 km. It is essentially a residential area with some minor parks, groves, fields, etc. There are several water level gauges and rainfall gauges in the catchment. Concerning the land use, ~65% of the surface is impervious. Rainfall from the upper part of the Kanda River catchment reaches the study catchment only by gravity flow through the combined sewer system. There is a main sanitary sewer along the Kanda River. During intense storms, this sewer soon flows full and discharges downstream of the catchment, which makes the catchments vulnerable to flooding.

(a)

(b)

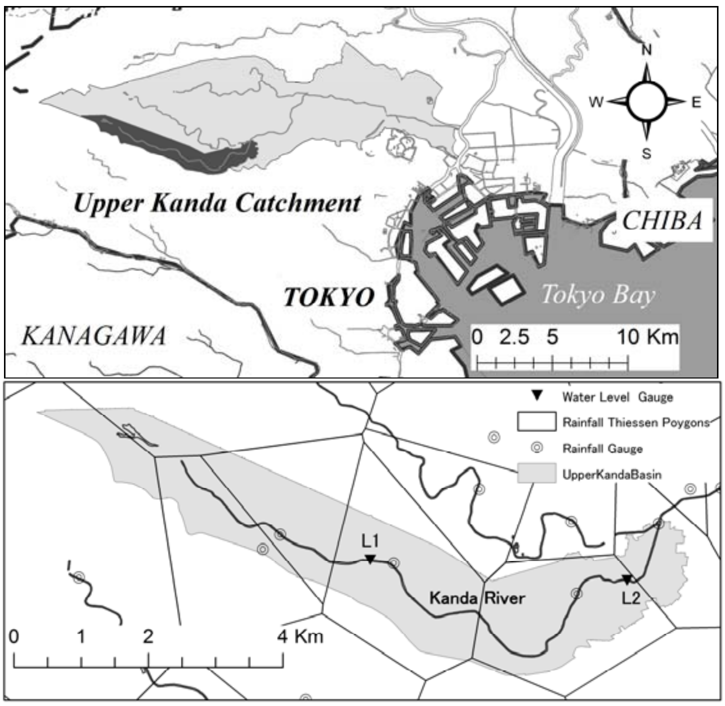

Figure 2: Location of the upper Kanda catchment in Tokyo and (a) and overview of the upper Kanda catchment selected for model application (b)

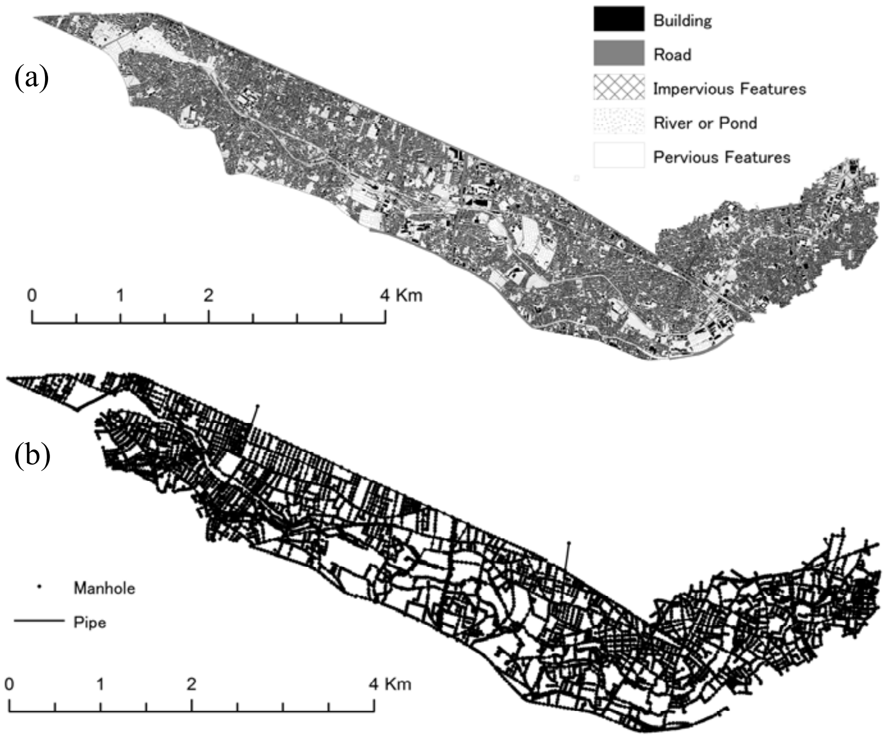

Figure 3: Final map of surface component (a) and sewer element (b) in the upper Kanda catchment

Figure 3 shows the final maps of surface component (a) and sewer element with road, block and river segments (b) in the entire study catchment. It should be emphasized that more than 180 000 homogeneous elements (land use, road, river, manhole and pipe) were used to completely specify the urban catchment.

To test the applicability of the TSR model for storm runoff analysis, simulations were performed for actual and hypothetical storm events. The first represents a small-scale event in which the storm water runoff in the sewer system was mainly free surface flow and no flooding occurred at 28^{th} August 2002. The second event represents a major flooding which followed hypothetical heavy rainfall which will be inundated parts of the catchment.

Concerning rainfall and runoff observations, there are several rainfall gauges in the catchment (Figure 2b), where observations are made with a 1-min time resolution by the Tokyo Metropolitan Government. Inside the upper Kanda catchment (Figure 2a), the average observed 60 minutes rainfall volume was 27 mm. Model results can be obtained at arbitrary locations, but for comparison with observations the locations of gauges L1 and L2 are used in the presentation of results below.

The initial water levels and discharge in the river channel were set at stationary conditions after an adequate model warm-up period during which river flow was calculated using the first observed river water data in an event. The initial water levels in the combined sewer system were approximated by the designed sewage flow conditions. Water levels in blocks and roads were set to zero as the simulation starts well before the start of the rainfall.

Table 1 shows the model parameters required. In this study, no attempt to calibrate or adjust parameter values is made but standard values are used. The initial loss parameters of impervious and pervious surfaces are obtained from Van de Ven (1992). The value of roughness coefficient used for building flow is 0.035 (Yen, 1991). The values of n used for surface flow are obtained from Inoue et al. (1998). The values were estimated based on model simulations of flooding in a similar type of urban catchment in Japan. The values of n used for sewer pipes and river channels are assigned as the standard roughness coefficient of concrete pipe (Mays, 2001).

Observed and simulated river discharge at gauge locations L1 and L2 are shown in Figure 4, together with the observed rainfall during the event. The simulated water river discharges in all two locations considered agree well with the observed levels throughout the event. The runoff peak at ~10:00 is well reproduced. The agreement

Table 1: List of required input data and parameters of the model

Parameter	Value	
Initial loss	Impermeable area	0.5
	Permeable area	1.0
Final infiltration capacity	Grove	100.0
	Grass	20.0
	Athletic field	5.0
	Others	5.0
Building roughness coefficient		0.030
Surface roughness coefficient	Roads	0.043
	Other	0.067
Pipe roughness coefficient		0.013

(a)

(b)

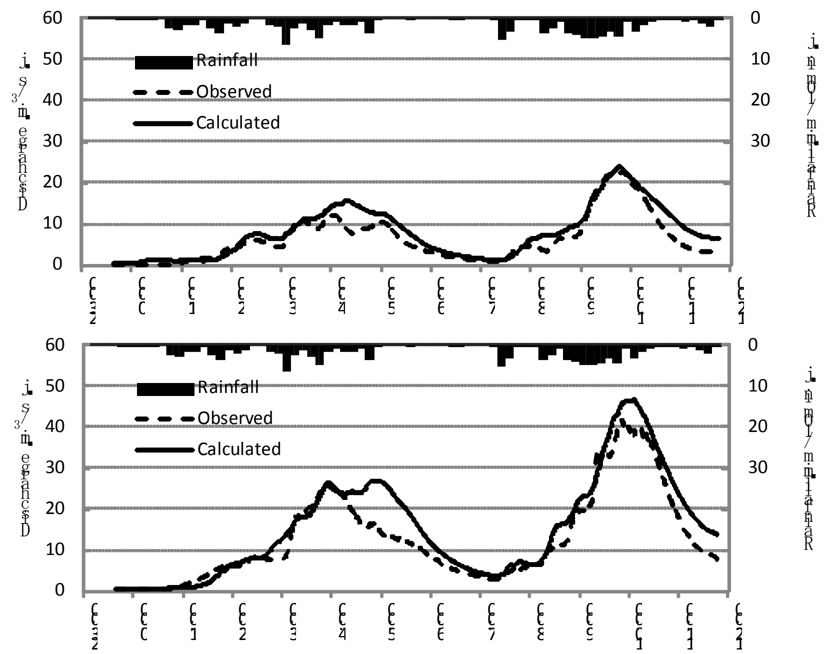

Figure 4: Observed and calculated discharge in gages L1 (a) and L2 (b)

appears at least reasonable considering the extreme nature of the event and the fact that no parameter calibration or other form of model tuning was used.

In order to evaluate also the model's ability to reproduce inundated conditions, a second runoff simulation was performed using a hypothetical rainfall event with 120 mm during 60 minuets. Figure 5 shows the hypothetical rainfall and simulated river discharge at the outlet of the upper Kanda River. Figure 6 shows an example of simulation results of maximum flood inundation area. The TSR model can also express the inundation process in a satisfactory way.

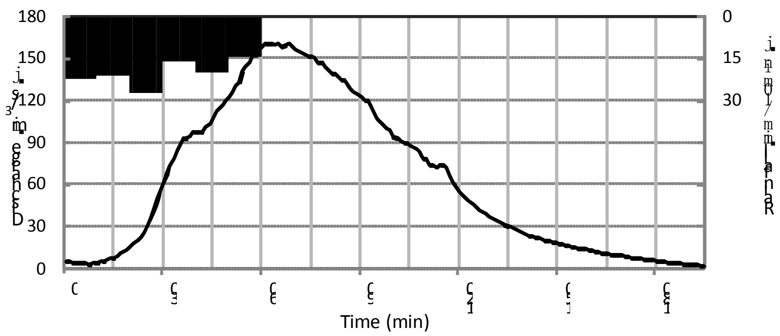

Figure 5: Simulated river discharge in the outlet of the upper Kanda River

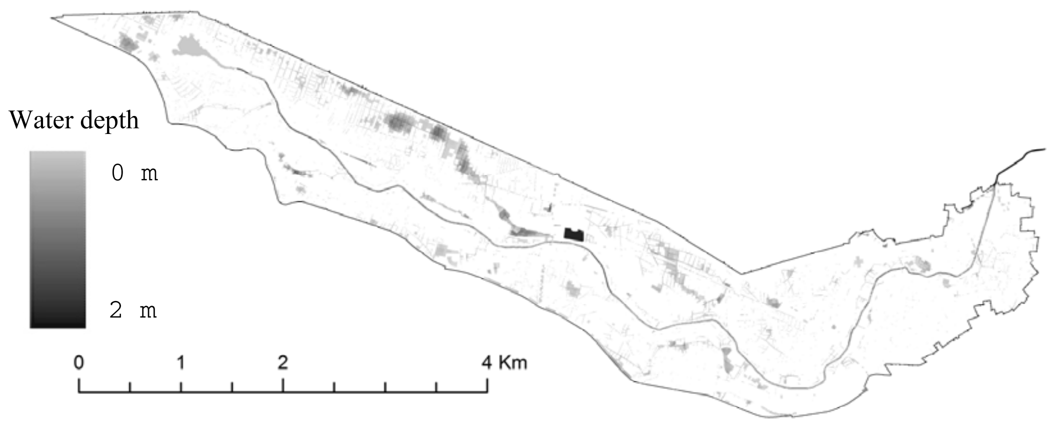

Figure 6: Maximum extension of inundated area

Conclusion

In this paper the Tokyo Storm Runoff (TSR) model, a vector-based distributed storm event runoff model, is applied for the upper Kanda catchment (11 km²) in Tokyo Metropolis, Japan. Model set-up is based on urban landscape GIS delineation that is used to faithfully describe the complicated urban land use features in detail. The model simulates both the conceptually different flooding processes related to overflow from a river and surcharge from a sewer system, respectively. The general model formulation was used with standard parameter values obtained from the literature. The simulated river discharge closely reproduced the observed ones.

In total, the results show that the applied approach, based on a detailed reproduction of all relevant elements in an urban catchment, is able to simulate all aspects of urban flooding. We believe the methodology has a wide range of application for many practical problems such as evaluation of measures to improve flood protection facilities, which may include river channel improvements as well as installation of new runoff control facilities. Another potential use of the model is detailed urban impact assessment of the higher rainfall extremes that are commonly expected in the future. The high level of detail used in the reproduction of the catchment is further very useful as it facilitates communication of the results, which is important in light of the recent trend towards increased stakeholder involvement in hydrological modeling.

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