Urban runoff analysis by the Tokyo Storm Runoff Model based on advanced GIS delineation

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Abstract The Tokyo Storm Runoff (TSR) model is developed and applied for urban runoff analysis. The set-up of this TSR model is based on so-called advanced GIS delineation that faithfully describes the complicated urban land use features in detail. The TSR model was set up and evaluated for the small urban lower Ekota catchment in Tokyo Metropolis, Japan. No calibration or tuning was performed, but the general model formulation was used with standard parameter values obtained from the literature. The runoff response to major storm event which inundated parts of the catchment was simulated. The simulated water levels closely reproduced the observed ones. Also the reported inundation area was well described by the model. Owing to its high level of detail as well as potential for result visualization, the model is well in line with the recent trend of increased stakeholder involvement in hydrological modeling.

Key words storm runoff model; urban catchment; advanced GIS delineation; flooding; Tokyo

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 an urban environment 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 new comprehensive model for urban storm runoff and flooding is developed and tested: the Tokyo Storm Runoff model. The modeling approach has been developed during recent years [e.g. Amaguchi & Kawamura, 2006; Amaguchi *et al.*, 2007] and is here presented in full, including two case studies. The model includes linked modules for direct runoff and flow on the surface, in the sewer system and in the river. The main novelty of this approach is that GIS is used in a more flexible way than in previous models, to allow for a faithful reproduction of an urban catchment. In the model, a catchment consists of four basic types of components – block, sewer, road and river – which are specified as polygons, lines or points representing their actual shape and location. In the paper, the associated GIS processing for this detailed catchment characterization, including connections between elements, is termed “advanced GIS delineation”. By this delineation, flow paths can be traced with a very high level of detail. The flow calculations in the different modules are all based on established concepts and equations. Non-inundated overland flow is simulated by a kinematic wave model, inundated overland flow and river flow by the unsteady flow equation, and sewer pipe flow by the Preissman slot model [Preissmann & Cunge, 1961]. As flow is calculated for single elements, a one-dimensional formulation of the equations is sufficient. The model is set up for an urban subcatchment of the Kanda River (Tokyo, Japan) and applied to simulate the runoff response to two actual storm events in 2005, one of which flooded part of the subcatchment.

In this paper, a comprehensive concept for detailed runoff modeling in an urban catchment is proposed. For that reason the hydrologic and hydraulic models used here are established standard models with standard parameter values obtained from the literature. Improving the descriptions of the different specific flow processes involved is thus outside the scope of the paper, but if desired it is straight-forward to replace the models below by more advanced alternatives.

THE TOKYO STORM RUNOFF (TSR) MODEL

The rainfall-runoff process

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 “advanced 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.

Fig. 1 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.

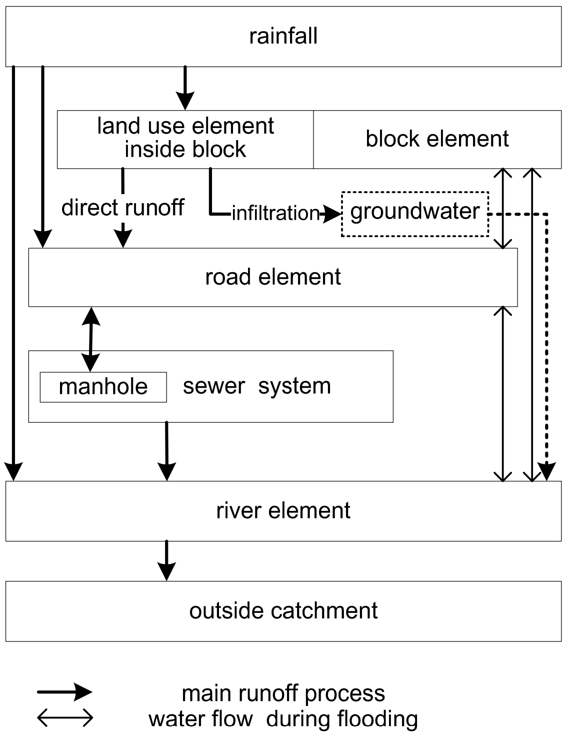

Fig.1 Schematic of the rainfall-runoff process.

Advanced GIS delineation

Fig. 2 shows an example of a detailed map of an urban catchment obtained by advanced 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 and others. In addition, advanced 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.

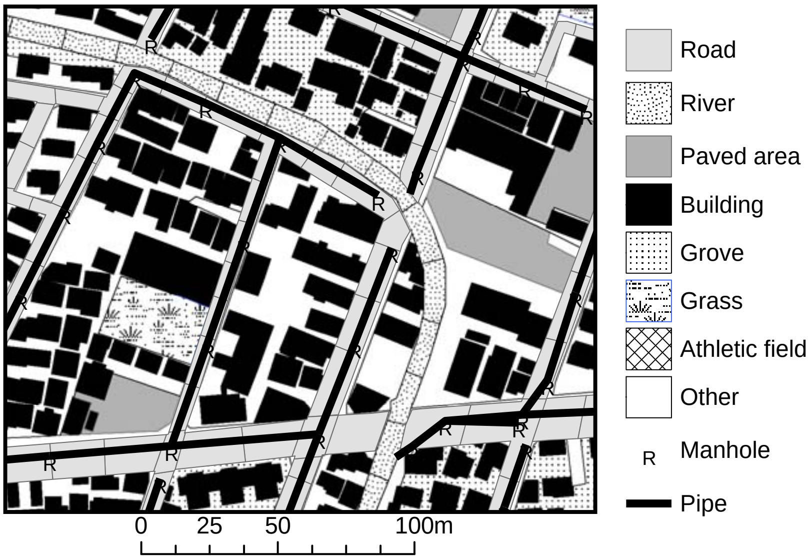

Fig.2 Map representing the different spatial elements considered in advanced GIS delineation.

MODEL APPLICATION

Study Area

The study area selected for the model application is a small urban catchment, which is located in the Kanda River basin Tokyo Metropolis, Japan, as shown in Fig. 3a. The study catchment will be termed “lower Ekota catchment” and Fig. 3b 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 lower Ekota catchment area is ~1.1 km^2 and the length of Ekota River inside it is ~1 km. It is essentially a residential area with some minor parks, groves, fields, etc. There are four water level gauges and one rainfall gauge in the catchment. Concerning the land use, ~60% of the surface is impervious. Along the lower

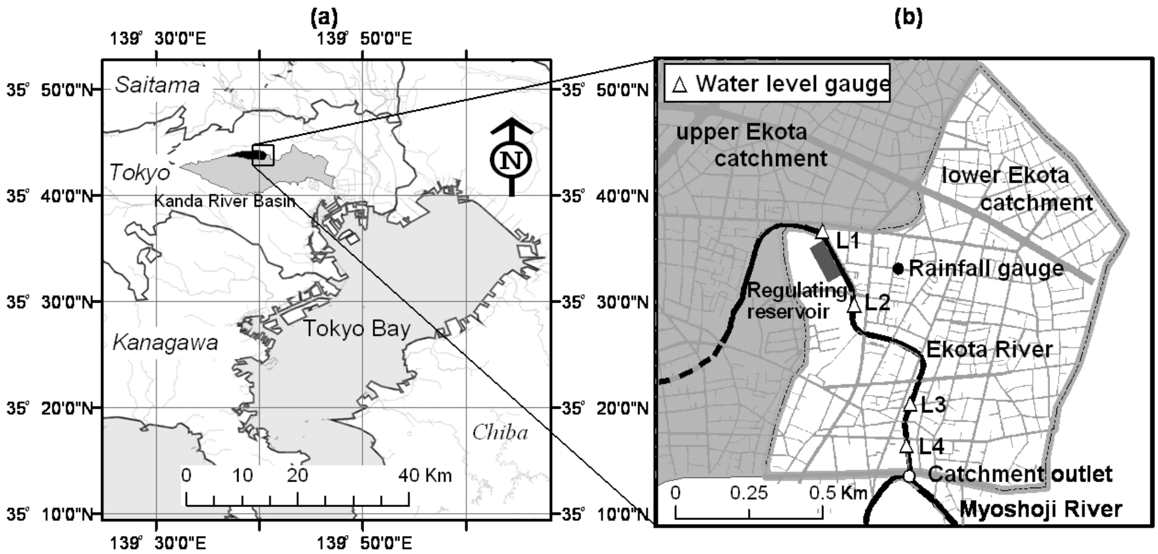

Fig.3 (a) Location of the Ekota catchment in Tokyo Prefecture, Japan and (b) overview of the lower Ekota catchment selected for model application.

Ekota River, between gauges L1 and L2, a regulating reservoir with side-spill weir exists on one side. Rainfall from the upper part of the Ekota River basin reaches the study catchment only by gravity flow through the combined sewer system. There is a main sanitary sewer along the Ekota River. During intense storms, this sewer soon flows full and discharges downstream of the catchment, which makes the catchments vulnerable to flooding.

Simulation of actual storm event 050904

On this day, typhoon nr. 14 in combination with a stationary front covering Japan produced a very heavy rainfall over the Ekota catchment as well as many other parts of Tokyo [Nomura, 2005]. Inside the Kanda River basin (Fig. 3a), the maximum observed 1-hr rainfall volume was 112 mm and more than 3700 houses were damaged by flooding [Nomura, 2005].

Concerning rainfall and runoff observations, there is one rainfall gauge in the catchment (Fig. 3b), where observations are made with a 1-min time resolution by the Tokyo Metropolitan Government. Model results can be obtained at arbitrary locations, but for comparison with observations the locations of gauges L2-L4 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 (one hour is enough in this catchment), during which river flow was calculated using the first observed river water data in each 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.

The river discharge at the upstream catchment border needs to be specified as a boundary condition. As a water level gauge exists at the upstream border, the boundary conditions here were estimated from a rating curve, calculated using observed water levels by taking into account the channel cross section and the average slope of the river bed. During event 050904, flooding occurred in the junction of Ekota River and Myoshoji River (Fig. 3b) and all the neighboring areas were submerged. Also backflow occurred due to a higher water level in Myoshoji River than in Ekota River. 1-min water level observations from downstream of the junction in the Myoshoji River are used as surrogate boundary conditions at the catchment outlet.

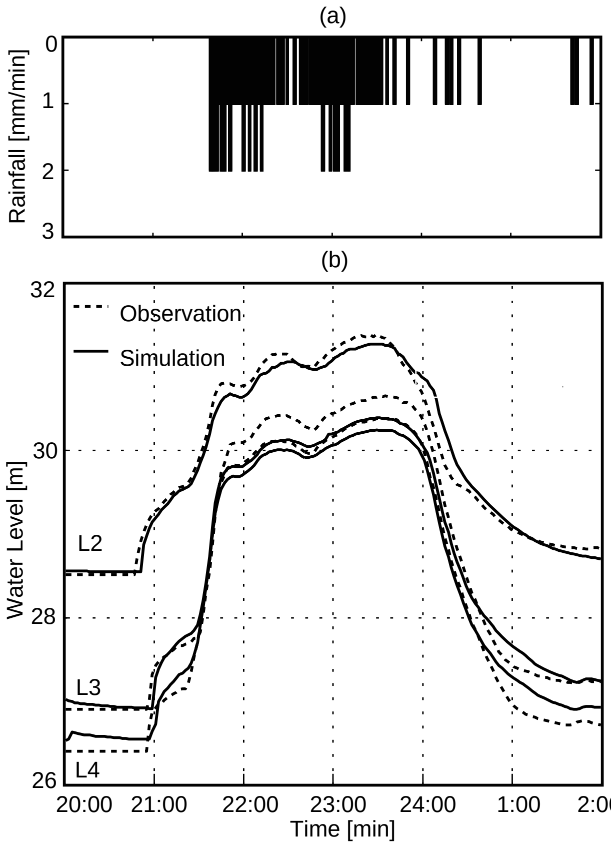

Fig.4 Observed rainfall (a) and observed and simulated river water level in gauges L2, L3 and L4 (b) during event 050904.

The results shown in Fig. 4 include the runoff contribution from the upper Ekota catchment. In the following, some properties of the locally generated runoff are presented and discussed. The objectives are to assess the realism of the results as well as to demonstrate what types of information the model is

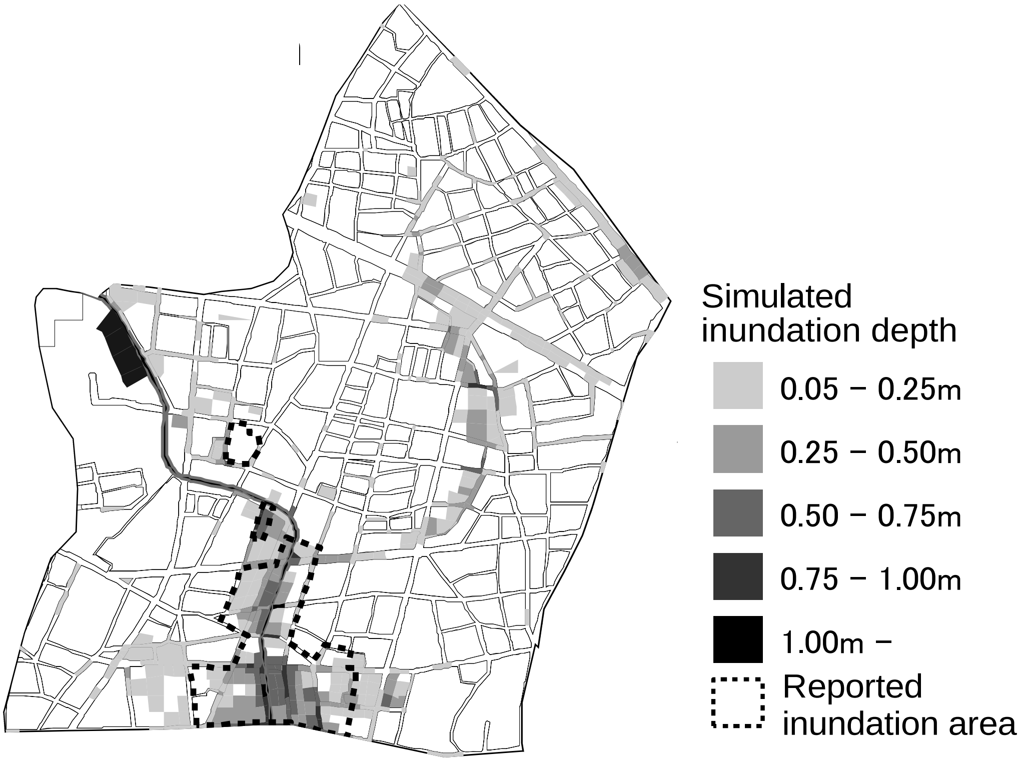

Fig.6 Maximum extension of inundated area.

flow out from the overland elements due to the inundated conditions.

The start of the rainfall at ~21:45, the water levels in both the manhole and the river abruptly increase as does the pipe discharge (Fig. 5f). At ~22:00 both the manhole and river water levels reach the level of the road. During the subsequent period of flooding, the water levels on the road, in the river and in the manhole are almost identical. However, although not clearly visible in Fig. 5e, the river water level becomes slightly higher than the road and manhole levels. This makes the pipe discharge negative for a 1.5-hr period starting ~22:30 (Fig. 5f). Thus, during the period of flooding river water entered the road both through the pipe and as direct overflow from the river.

Fig. 6 shows the maximum extension of the inundated area, defined as the maximum inundation depth in each block or road element (>5 cm) during the flooding event. Showed in the Fig. 6 is also a reported inundation area. This is based on a questionnaire that was distributed after the event, in which residents were asked to report damages caused by the flooding. As the area shown thus represents locations where damages were reported, and not any observed water depths, it must be considered only a rough estimate of the extension of the flooding. Even so, there is a reasonable agreement between simulated and reported inundation, with the reported area covering most of the locations that were severely inundated in the model simulation. No damages were reported along the main sewer, which is at least partly owing to the existence of a large park in this area. This is designed to have a retention function during flooding events, and this function can thus be considered verified in Fig. 6, indicating a water depth between 25 and 50 cm in the park. It may be remarked that no similar retention facility exists in the close vicinity of the catchment outlet, which could potentially have reduced the reported damages.

CONCLUSIONS

In this paper the Tokyo Storm Runoff (TSR) model, an urban catchment storm runoff model, is developed and tested. Model set-up is based on advanced 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 model was set up and evaluated for the small urban lower Ekota catchment (1.1 km^2), Tokyo Metropolis, Japan. No calibration or tuning was performed, but the general model formulation was used with standard parameter values obtained from the literature. The simulated water levels closely reproduced the observed ones. The reported inundation area was well described by the model. It was also demonstrated how the model can be used to evaluate the flow conditions in specific components of the urban hydrological system as well as to verify the function of flood-preventive structures.

In total, the results show that the suggested approach, based on a detailed reproduction of all relevant elements in an urban catchment, is able to simulate all aspects of urban flooding with high accuracy. Although in principle relatively straight-forward, this type of approach has until now not been practically attainable because of limitations in the resolution of available GIS data as well as limitations in computer power. 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. Such proposed modifications may be easily implemented in the advanced GIS delineation and their function evaluated. 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. The conditions at specific critical locations can be easily extracted from the model output and used during discussions with the stakeholders involved.

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