Evaluation of Climate Change Impacts on Urban Drainage Systems by a Storm Runoff Model with a Vector-Based Catchment Delineation

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Abstract:

Problems with efficient dewatering following heavy rainfall events are not uncommon already today because of urbanization beyond the sewer system capacity. Sewer drainage system evaluation are required in many cities and a key issue in this situation is whether to take climate change into account. In this study a simulation model for rainfall-runoff and flood inundation model with a vector-based catchment delineation are used. The set-up of this model is based on so-called “urban landscape GIS delineation” that faithfully describes the complicated urban land use features in detail. Modelling was performed using as inputs design storm with 3 year return periods of 180 minutes duration for climate change scenarios. These future design storms were increased by factors of 10%, 20%, 30%, and 40% and the impacts of incremented rainfall events on the urban drainage system were assessed. It was indicated that the surface runoff would increase at higher percentages than infiltration loss and final surface storage.

INTRODUCTION

A general expected consequence of climate change is an increase of extreme rainfall intensities in short time based on theoretical reasoning. Climate change is expected to an increase in frequency and intensity of heavy rain fall events (Maihot et al. 2010). Problems with efficient dewatering following heavy rainfall events are not uncommon already today because of urbanization beyond the sewer system capacity.
Olsson et al. (2012) assessed the climate change impacts on urban storm water at Arvika, Sweden. They indicated an increase in today’s short-term extreme rainfall of 10-30 % by the end of the century. The urban drainage system upgrade to accomplish full performance for the future design storm would cost around twice.

The Japan weather association (2012) reported a 1.15°C increase in average temperature in Japan since 1900. Based on the report, the overall precipitation has increased across Japan during the period 1900-2010. The global climate models point out that global mean rainfall will increase with global warming, even though spatial distribution and seasonal variations are exist.

Urban sewer drainage system is expected to deal with flood infrastructure designs on the base of appropriate amenity level. Current infrastructure design is principally based on rainfall Intensity-Duration-Frequency (IDF) curves with the stationary assumption. Due to change in the frequency of extreme rainfall, for the capability of urban drainage systems, the current IDF curves will no longer be valid, requiring an adjustment for climate change (Arnbjerg, 2006). There is more concern how to deal with the future climate change in the urban local municipalities. The stakeholders should make their mitigation measure based on the reliable and accurate evaluation tool.

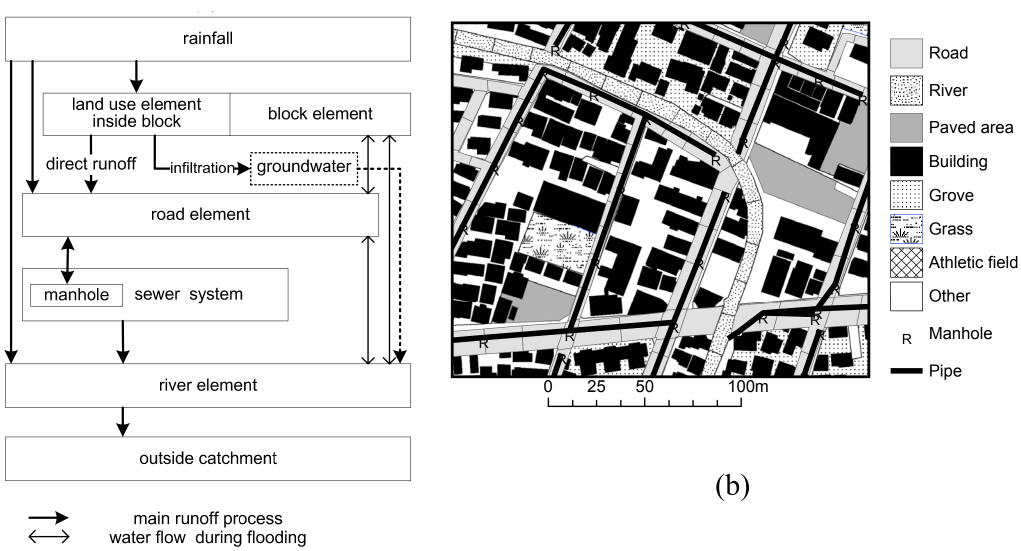
The aim of this study is to assess the impact of climate change on the drainage system for an urban catchment in Tokyo, Japan. In this study, a simulation model for rainfall-runoff and flood inundation model with a vector-based catchment delineation are used (Amaguchi et al. 2012). The set-up of this model is based on so-called "urban landscape GIS delineation" that faithfully describes the complicated urban land use features in detail. Modelling was performed using as inputs design storm with a return period of 3 years.

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 1a 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 1b 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 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.



(a) (b)

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

CASE STUDY URBAN CATCHMENT

The study area selected for the model application is an 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.

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.

(a)

(b)

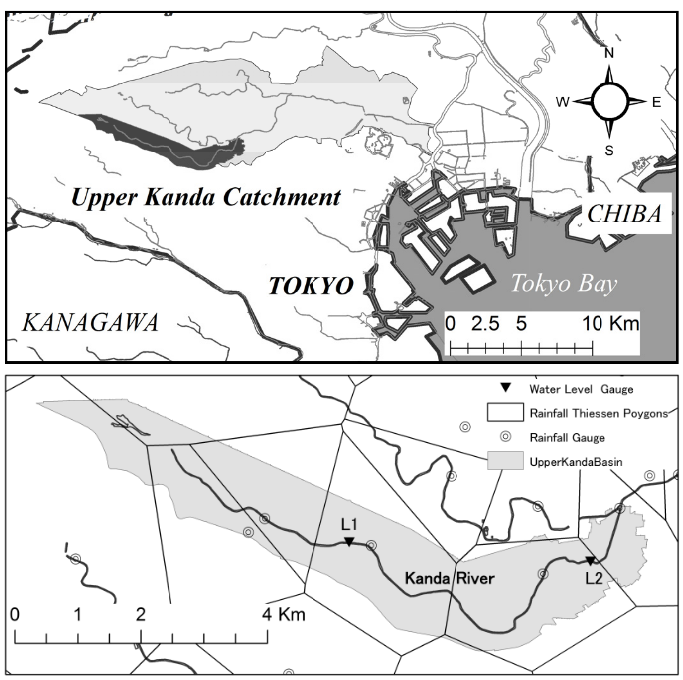


Figure 2. Location of the upper Kanda catchment in Tokyo and (a) and overview of the catchment selected for model application (b)

MODEL CALIBRATION

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 28th August 2002. The second event represents a major flooding which followed hypothetical heavy rainfall which will be inundated parts of the catchment.

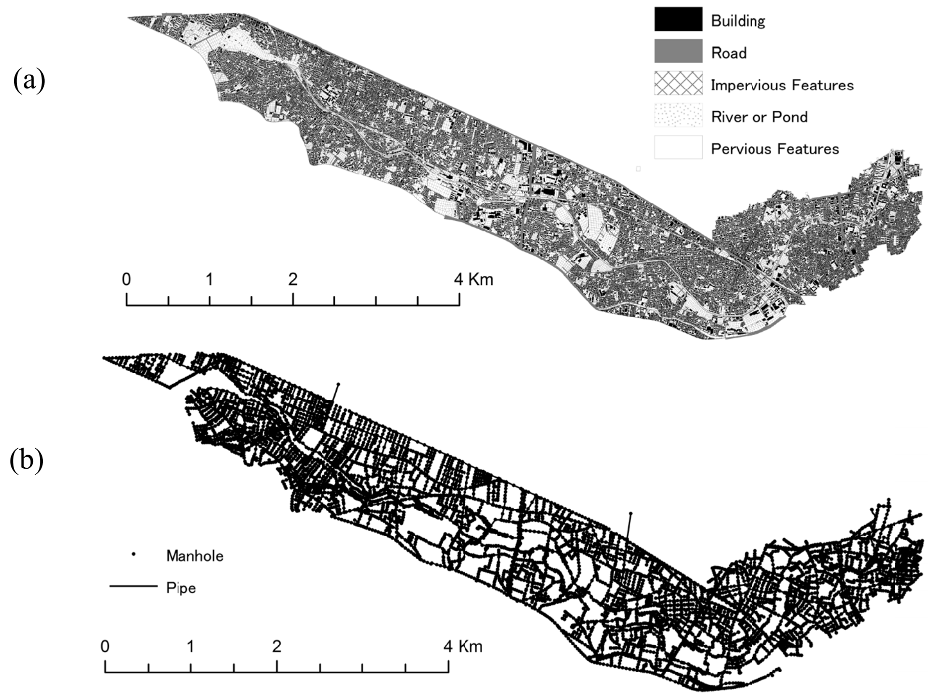


Figure 3. Final map of surface component (a) and sewer element (b) in the upper Kanda catchment

Concerning rainfall and runoff observations, there are several rainfall gauges in the catchment (see 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).

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

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 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.

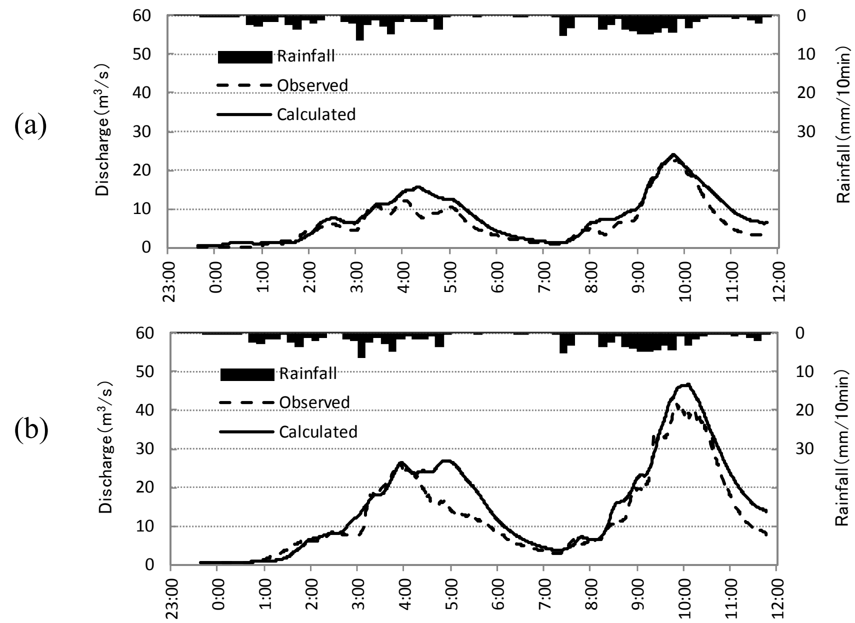


Figure 4. Observed and calculated discharge in gages L1 (a) and L2 (b)

CLIMATE CHANGE SCENARIOS

In this study the available historical annual maxima rainfall series of duration 10 and 60 minutes for the period from1940 to 2015 for the Tokyo rain gauge were provided by Japan weather association (see Figure 5a). For the IDF curve definition, the Generalized Extreme Value (GEV) distribution was used. The GEV is a continuous probability distribution which combines the Gumbel, Frechet, and Weibull distribution. It is often used to model extreme rainfall based on extreme value theory (Coles et. al., 2001). In this study GEV parameters were estimated using L-moment (Hosking and Wallis, 2009). For the historical dataset (1940-2015), 20 years continuous sub-dataset with different ending years were sampled and 10 and 60 minutes rainfall for return period equal to 3 years was estimated (see Figure 5b). In regards to the 60 minutes rainfall, the value showed 32% increase, increasing from 40.7mm (1980) to 53.8mm (2015).

To evaluate the design rainfall for the 2100 projection, the result of future storm rainfall intensity which is analyzed using GCM20 model. Kashiwai et al. (2008) indicated the change of the maximum annual hourly rainfall would be -30% to 40% (2100) for over the study area. In this study, a senility analysis of the urban drainage system for current IFDs by 10%, 20%, 30% and 40% is proposed for evaluation of the existing urban drainage system against climate change (see Figure

6). The 3 hours duration events having 3 years return period rainfall is extracted from IFD curve for Tokyo rainfall station. The 180minutes event was used as the base line for the methodology of implementation of climate change scenarios.

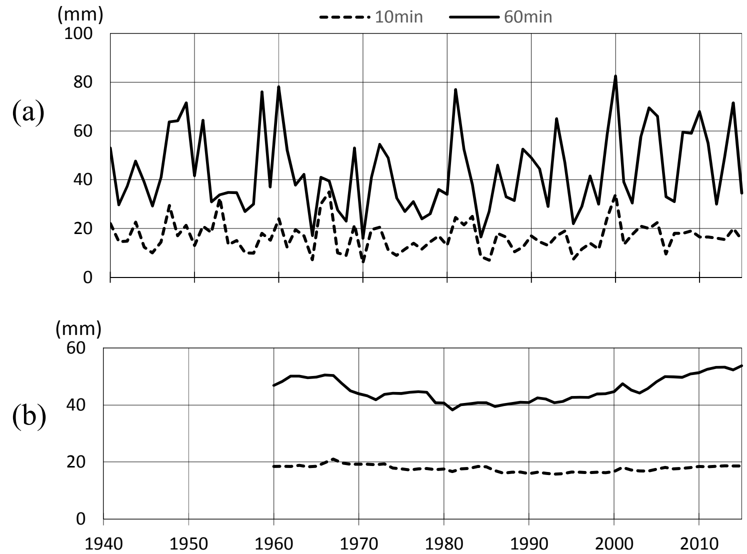


Figure 5. Annual maximum 10 and 60 minutes rainfall (a) and their values for return period equal to 3 years estimated by GEV distribution (b).

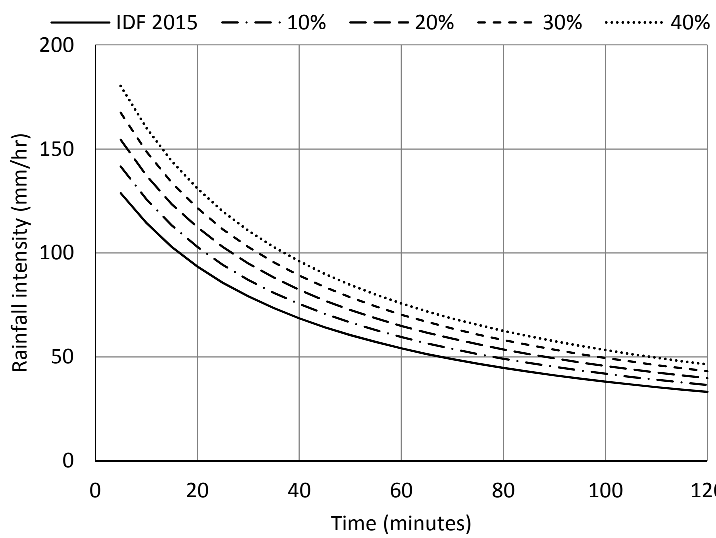


Figure 6. Current IDF curve for T=3 years (1995-2015) and increase in current IDF by 10, 20, 30 and 40 %.

Table 2 shows the results of the TSR model assessment for the climate change scenarios. For the event having 3 years return period and a 40% increase in the volume of rainfall, the infiltration would increase by about 10%, while the surface direct runoff would increase by around 47%. The increase in final surface storage is substantially less than the surface direct runoff, with an increase of around 30%. The increase in number of flooded manholes would reach approximately 200%. The results of the TSR model analysis showed above indicate that the increase in the surface direct runoff is quite larger than the increase in infiltration and storage capacity.

	+ 0%	+ 10%	+ 20%	+ 30%	+ 40%
Total Precipitation (mm)	71.5	78.6	85.8	92.9	100.1
Infiltration Loss (mm)	13.5	13.9	14.3	14.6	14.8
Surface Runoff (mm)	58.0	64.7	71.5	78.3	85.3
Final Surface Storage (mm)	4.2	4.6	4.9	5.2	5.5
Flooded Manholes	570	828	1090	1389	1687

DISCUSSION AND CONCLUSION

In this study, TSR model was used for the case study urban catchment and several scenario of future climate change were implemented to evaluate its impact on the urban drainage system. The analysis presented in this study evaluated the urban drainage system by simple climate change scenarios with 180 minutes duration design rainfalls of 3 year return periods. These future design rainfalls were increased by factors of 10%, 20%, 30%, and 40% and the impacts of incremented rainfall events on the urban drainage system were assessed. It was indicated that the surface runoff would increase at higher percentages than infiltration loss and final surface storage. It may be conclude that future increased rainfall intensity due to climate change might have a substantial impact on the performance of the urban drainage system in the Upper-Kanda Catchment.

Another potential use of the model is detailed urban impact assessment of the higher rainfall extremes that are commonly expected in the future. 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. 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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