

Impact of Urbanization on Rainfall-Runoff Processes: Case Study in the Liangshui River Basin in Beijing, China

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Abstract China is undergoing rapid urbanization during the past decades. For example, the proportion of urban population in Beijing has increased from 57.6% in 1980 to 86.3% in 2013. Rapid urbanization has an adverse impact on the urban rainfall-runoff processes, which may result in the increase of urban flood risk. In the present study, the major purpose is to investigate the impact of land use/cover change on hydrological processes. The intensive human activities, such as the increase of impervious area, changes of river network morphology, construction of drainage system and water transfer, were considered in this study. Landsat TM images were adopted to monitor urbanization process based on Urban Land-use Index (ULI). The SWMM model considering different urbanized scenarios and anthropogenic disturbance was developed. The measured streamflow data was used for model calibration and validation. Precipitation with different return periods was taken as model input to analyse the changes of flood characteristics under different urbanized scenarios. The results indicated that SWMM provided a good estimation for storms under different urbanized scenarios. The volume of surface runoff after urbanization was 3.5 times greater than that before urbanization; the coefficient of runoff changed from 0.12 to 0.41, and the ratio of infiltration decreased from 88% to 60%. After urbanization, the time of overland flow concentration increased while the time of river concentration decreased; the peak time did not show much difference in this study. It was found that the peak flow of 20-year return-period after urbanization is greater than that of 100-year return-period before urbanization. The amplification effect of urbanization on flood is significant, resulting in an increase of the flooding risk. These effects are especially noticeable for extreme precipitation. The results in this study will provide technical support for the planning and management of urban storm water and the evaluation on Low Impact Development (LID) measures.

Key words Urbanization; rainfall-runoff; SWMM model; Liangshui River

1. INTRODUCTION

Urbanization is an important index to reflect the development level of a country, but it also enhances the interaction between human society and the environment. The unbalance of the water conservancy facilities transformation and the rapid urban development resulted in considerable urban water problems in China. From 2008 to 2010, different kinds of floods and inundation disasters occurred in 62% of cities in China. For example, the heavy rainfall on July 21, 2012 in Beijing, resulted in 63 severe urban inundations and claimed the lives of 79 people.

Urbanization increases the risk of flooding due to increased peak discharge and volume, and decreased time to peak that restricted the development of cities (Nirupama *et al.*, 2007; Saghafian *et al.*, 2008). In highly urbanized areas, over half of rainfall becomes surface runoff, and deep infiltration is only a small fraction of natural situation (Chester *et al.* 1996). However, some researchers did not found significant changes in runoff coefficients in an urbanized catchment (Brun and Band, 2000; Chang, 2003). Rainfall-runoff process is known to be related to complex factors in urban catchment, such as land use/cover, river network morphology, construction of drainage system and water transfer. The complexity of underlying surface, the uncertainty of anthropogenic disturbance, and the lack of high-quality datasets for calibration and validation may limit our research for the rainfall-runoff processes in an urban catchment. Thus, there is an urgent need to develop a hydrological model to identify the impact on urbanization with a support of long-term monitoring data in a typical urbanized catchment.

A variety of hydrological models have been developed and applied to simulate rainfall-runoff processes in urban area, including SWMM, MIKE, HSPF, STORM and INFOWORKS. For instance, Guan *et al.* (2015) used the SWMM model to simulate a series of scenarios in a developing urban catchment. Koudelak *et al.* (2008) and Peng *et al.* (2015) adopted the InfoWorks model to simulate sewerage network flow in the city of Latvia and China, respectively. Guo *et al.* (2013) and Alam *et al.* (2014) used MIKE model to assess flood hazard combined sewer system in urban areas.

In this study, SWMM model considering different urbanized scenarios and anthropogenic disturbance was developed on the basis of remote sensing image and survey. The measured streamflow data was used for model calibration and validation. Precipitation with different return periods was taken as model input to analyse the changes of rainfall-runoff process under different urbanized scenarios.

2. STUDY AREA DESCRIPTION

Dahongmen catchment (*Fig. 1*) is located in the upstream of Liangshui River basin in Beijing, between 39°48'-39°55'N, 116°9'-116°24'E and with an area of 131km². The terrain in the catchment shows a downward trend from the western mountains to the eastern plains. The annual average precipitation is 522.4 mm and 80% of precipitation occurs during the period from June to September. Dahongmen catchment, which has experienced a rapid urbanization process over the past two decades, has gradually become a transport hub and core zone of Beijing metropolitan. Floods and inundation frequently occur in this area, which was further intensified after rapid urbanization. For the purpose to solve this problem, a set of anthropogenic measures including water transfer, river and sewer system, and morphology changes were taken. However, these measures further changed the local rainfall runoff processes.

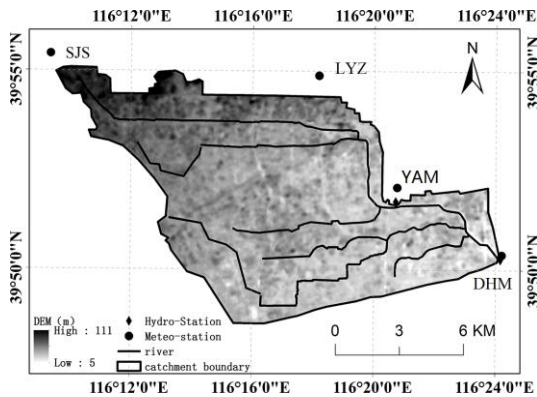


Fig. 1 Location, river systems, and hydro-meteorological stations in the Dahongmen catchment

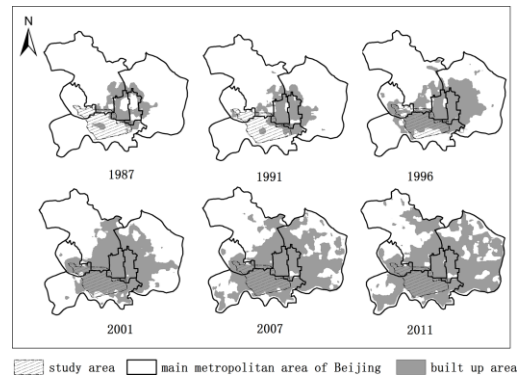


Fig. 2 Urbanization processes in the Dahongmen catchment

3. MODEL AND DATA DESCRIPTION

3.1 SWMM model

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. It was first developed in 1971 and continued to be widely used throughout the world for planning, analysis and design related to storm water, combined sewers, and other hydraulic structures in urban areas. The main components of SWMM include surface runoff, infiltration, surface concentration, channel and pipe concentration and LID controls. Further technical details of the model are given by Rossman *et al.* (2010).

3.2 Data description

In this study, urban land-use index (ULI) was used to monitor the urbanization process of Dahongmen catchment in Beijing (*Fig. 2*). ULI is an effective index automatically extracting from urban land uses with Landsat 7 image. It reduces the impact of low density vegetation on extraction accuracy. According to Fig.2, the study area has experienced rapid urbanization process from 1987 to 2011, and the proportion of impervious area in SWMM model is set based on ULI index.

Digital Elevation Model (DEM) and sewer system map were provided by the National Aeronautics and Space Administration (NASA, ASTER GDEM) and Beijing Municipal Institute

of City Planning and Design. Hourly precipitation series at 4 stations (Fig. 1) and streamflow data at DHM station from 1980 to 2012 were obtained from the Hydrographic Station of Beijing. Hourly inflow data of YAM station were obtained from the Liangshui River Basin Authority.

4. MODEL DEVELOPMENT

4.1 Catchment subdivision

Catchment subdivision should reflect the urbanization process and has great impacts on the rainfall runoff simulation. Before urbanization, DEM and D8 algorithm were used to extract the subcatchment (Fig.3). But for highly developed urban area, catchment was divided by design drainage areas provided by the Beijing Municipal Institute of City Planning and Design.

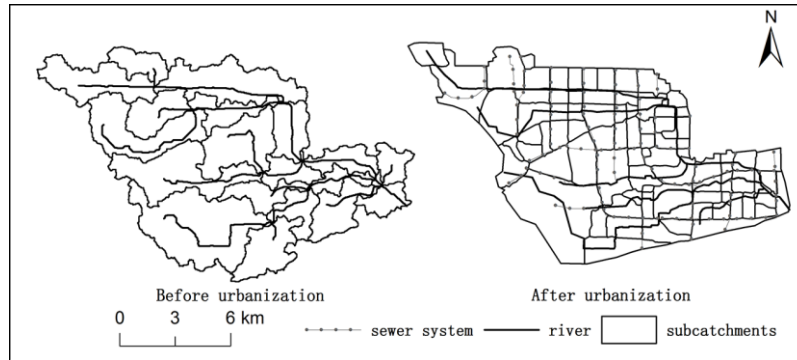


Fig. 3 Model development in different urbanization cases

4.2 Model accuracy evaluation

According to the standard for hydrological information and hydrological forecasting in China, Nash-Sutcliffe efficiency coefficient (R_{NS}), relative error of flood peak discharge (RE_p) and absolute error of flood peak appearance (AE_T) were used for measuring the accuracy of model performance.

$$R_{NS} = 1 - \frac{\sum_{i=1}^N (q_t^{obs} - q_t^{sim})^2}{\sum_{i=1}^N (q_t^{obs} - \bar{q}^{obs})^2} \quad (1)$$

Where q_t^{obs} is observed discharge sequence, N is the number of observed discharge data and \bar{q}^{obs} is the average of the observed discharge.

$$RE_p = \frac{|q_p^{obs} - q_p^{sim}|}{q_p^{obs}} \times 100\% \quad (2)$$

Where q_p^{obs} is the observed peak flow, q_p^{sim} is the simulated peak flow.

$$AE_T = T_p^{obs} - T_p^{sim} \quad (3)$$

Where T_p^{obs} is the observed occurrence time of flood peak, T_p^{sim} is the simulated occurrence of flood peak.

5. RESULTS ANALYSIS

5.1 Model calibration and validation

Most of the parameters in SWMM model have its specific physical meaning, which can be measured theoretically. Due to the limitation of data, these parameters are usually determined by empirical method or optimization method. In this study, the genetic algorithm (GA) was adopted to optimize the sensitive parameters in SWMM model, and Nash-Sutcliffe efficiency (R_{NS}) was used as the objective function. Results of parameter identification are given in Table 1

Table 1 Results of parameter identification

Parameters in SWMM		Before urbanization	After urbanization
Manning coefficient	Pervious zone	0.43	0.36
	Impervious zone	0.07	0.04
	Channels	0.025	0.048
	Pipeline	/	0.02
Horton coefficient	Maximum infiltration	124.6	142.4
	minimum infiltration	74.7	89.6
	Decay coefficient	11.4	23.2

Manning coefficient in both pervious and impervious area decreased after urbanization, it shows that the concentration time of overland flow declined. However, the increase in manning roughness coefficient of channel suggested that the concentration time of river raised after urbanization. Horton infiltration coefficient reflects the infiltration capacity of pervious zone, which changes little after urbanization. Error statistics of simulation results and flood hydrograph are shown in Table 2, Fig. 4 and Fig. 5.

Table 2 Error statistics of simulation results

		Calibration		Validation	
Before urbanization	Storm	19810703	19830619	19850702	19870813
	R _{ns}	0.62	0.61	0.83	0.64
	RE _p	3%	3%	6%	15%
	AE _T	-1	0	0	+1
After urbanization	Storm	20110623	20120721	20110814	20110726
	R _{ns}	0.88	0.95	0.84	0.60
	RE _p	2%	2%	11%	4%
	AE _T	0	0	+1	0

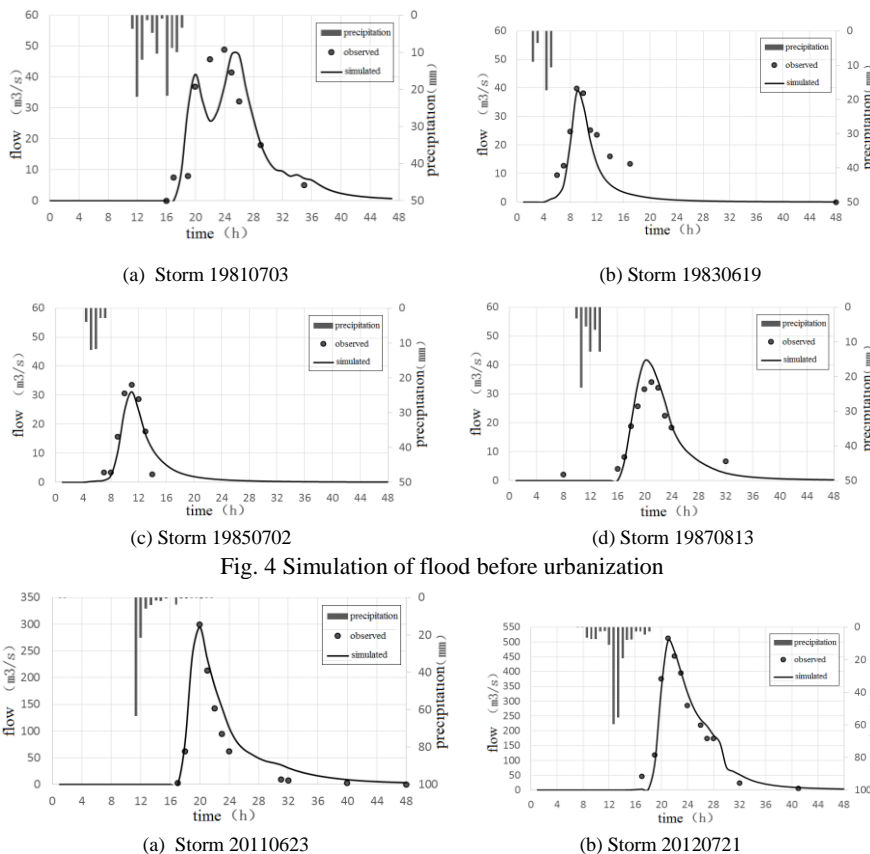


Fig. 4 Simulation of flood before urbanization

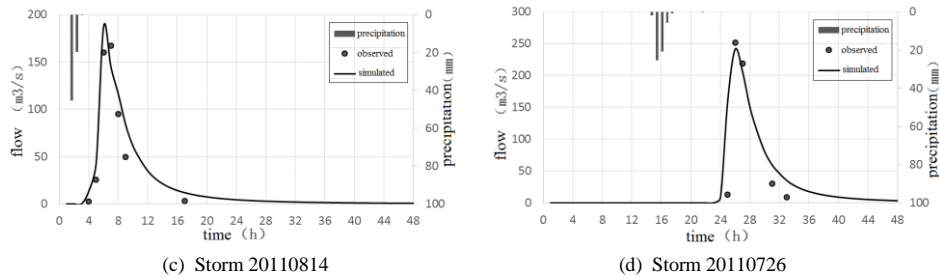


Fig. 5 Simulation of flood after urbanization

As can be seen, Nash-Sutcliffe efficiency is greater than 0.6 and the relative error of the peak flow is smaller than 15% in both calibration and validation periods, which means that SWMM provided a good estimation both pre- and post-urbanization. Moreover, the simulation results after urbanization are much better than before, particularly on the occurrence time of flood peak.

5.2 Rainstorm scenario analysis

According to the hydrological handbook in Beijing, the design storms with different return periods ($p=100\%$, $p=20\%$, $p=5\%$, $p=2\%$, $p=1\%$) were calculated based on design rainfall formula and the 24-hour rainfall distribution. The results of design storms are given in Fig.6. Changes of floods in different urbanization scenarios were simulated with these input precipitation data and the results are shown in Fig. 7 and Table 3.

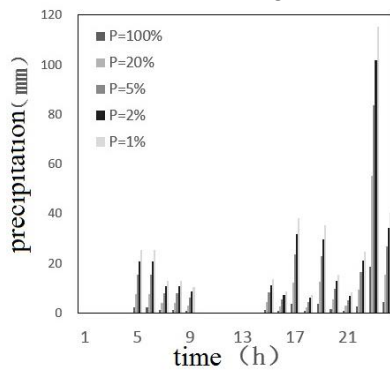


Fig. 6 24 hour-rainfall processes at different frequency

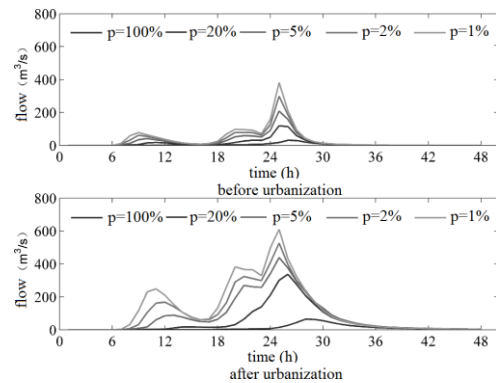


Fig. 7 Changes of floods in different urbanization scenarios

Table 3 Changes of rainfall-runoff processes in different scenarios

Hydrological Various	P=100%		P=20%		P=5%		P=2%		P=1%	
	before	after	before	after	before	after	before	after	before	after
Precipitation (mm)	47.7	47.7	150.4	150.4	260.3	260.3	335.9	335.9	395.0	395.0
Runoff (mm)	5.5	14.6	17.9	66.3	30.3	109.8	40.0	136.3	48.6	161.1
Runoff-Coefficient	0.12	0.31	0.12	0.44	0.12	0.42	0.12	0.41	0.12	0.41
Peak flow (m^3/s)	30.6	64.3	118.7	337.4	208.5	438.6	298.8	526.7	384.9	612.8
Peak time (hour)	3h	5h	2h	3h	2h	2h	2h	2h	2h	2h

According to Table 3, the urbanization process has a significant amplification effect on runoff generation. Taking 100-year return-period ($p=1\%$) as an example, the surface runoff after urbanization is 395mm, which is 3.55 times than that before urbanization. The runoff coefficient increased from 0.12 to 0.41, and the infiltration after urbanization covers 65% of that before

urbanization; however, the peak flow after urbanization is 1.68 times than that before urbanization. Therefore, the amplification effect of urbanization on low-frequency flood is obvious, resulting in an increase of the flooding risk in urban area.

However, the flood peak did not appear earlier, and even delayed on high-frequency precipitation ($p=100\%$ and $p=20\%$). Field investigation found that there are many artificial river barrages (such as bridges, gates or embankments) which delayed the time of channel concentration. On the other hand, the runoff flowed along the artificial path after urbanization, which makes it faster but longer than that before urbanization, and hence influenced the peak time. It is also found that the peak flow of 20-year return-period after urbanization is higher than that of 100-year return-period before urbanization, which puts forward new requirements and challenges for the transformation of urban facilities and urban water management.

6. CONCLUSIONS

In this study, the SWMM model considering different urbanized scenarios and anthropogenic disturbance was successfully applied to simulate the rainfall-runoff process in Dahongmen catchment, Beijing. The measured streamflow data was used for model calibration and validation. Precipitation with different return periods was used as model input to analyse the changes of flood characteristics under different urbanized scenarios. Major conclusions can be summarized as follows:

- (1) SWMM model has good performance for the simulation of rainfall-runoff process before and after urbanization. Nash-Sutcliffe efficiency is greater than 0.6, and the relative error of flood peak discharge is smaller than 15% both during calibration and validation periods.
- (2) The volume of surface runoff after urbanization was 3.5 times greater than that before urbanization; the coefficient of runoff changed from 0.12 to 0.41, and the ratio of infiltration decreased from 88% to 60%. The amplification effect of urbanization for low-frequency precipitation is more obvious and the peak flow of 20-year return-period (5%) after urbanization is higher than that of 100-year return-period (1%) before urbanization, leading to a higher flood risk in urban area.
- (3) The occurrence time of flood peak shows little change after urbanization. The concentration of overland flow accelerates and the river concentration had grown over time after urbanization. Therefore, the occurrence time of flood peak did not appear in advance or even delayed on high-frequency precipitation ($p=100\%$ and $p=20\%$), mainly due to the growing number of artificial river barrages in the study area.

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