Influence of underlying surface changes on flood characteristics of Xiaoqing River in Shandong Province, China using HEC-HMS model

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Abstract. The hydrological characteristics of the Xiaoqing River Basin (above Chahe Hydrological Station) in Shandong Province, China are changing due to increased urbanization. It has been found that since 1985 the constructed land area in the river basin has increased by 119% in 2015. Any changes in the river basin may increase the flood frequencies which may have severe consequences downstream of the river. We simulated the influence of underlying surface changes on flooding in the Xiaoqing river basin. The hydrological model HEC-HMS, a rainfall-runoff simulation model, was used to simulate the flood volume and the peak discharge values under the two underlying surface conditions in 1985 and 2015. The results indicated that influence of increased urbanization in 2015 increased in the flood volume and the peak discharge by approximately 17.8% and 15.4% on average respectively. Also the runoff R increases by 0.0058 mm for each unit increase of CN value under the unit rainfall.

1. Introduction

Underlying surface of a watershed is a complex of multiple factors, mainly means its land use, soil type, topography, geological structure, and rock property [1]. The United Nations Development Program (UNDP) predicts that 70% of the world’s population will live in urban areas by the year 2050 [2,3]. Certainly, urbanization process will cause intense changes on underlying surface, thus affecting the flood characteristics at the basin scale. Many scholars have investigated the influence of underlying surface changes on basin flood characteristics, and the results indicate that a considerable part of basin areas have been becoming impervious caused by continuous expansion of urban construction scale, which could lead to decreasing rainfall infiltration, accelerating response of runoff to rainfall, shortening return period of small floods, and etc., and thus the risk of storm flood increased greatly [4-9]. On the basis of previous researches, coupling basic data of DEM, soil type, remote sensing, rainfall, and secondary flood, we firstly used the SCS Curve Number approach to quantitatively estimate the conditions and changes of different underlying surfaces, secondly, according to the calculation results of which, we selected hydrological model HEC–HMS to simulate and calculate generation and confluence of different rainfalls under different underlying surface conditions, analysed the impacts of underlying surface changes on flood characteristics, and quantified...
the correlation between rainfall, runoff and underlying surface change, aimed to further reveal the influence mechanism of underlying surface change on hydrological process and provide scientific basis and decision support for boosting urbanization process scientifically and rationally and preventing and controlling urban flood disasters.

2. Study area and datasets

2.1. Study area
We have considered the middle and upper reaches of Xiaoqing River basin (above Chahe hydrological station) located in the north-central part of Shandong Province, China as the study area, which is about 5450 km². The topography is high in the South and West and low in the North and East, with altitudes ranging from 5 to 892 m (1956 Huanghai elevation) (figure 1). The study area includes most regions of Jinan, Zibo, Zhangqiu, Zouping and Huantai, whose urbanization process began in the early 1980s, and continued after the 1990s, reaching its peak around 2010 [10]. After the severe flood disaster on July 18, 2007, the government strengthened its comprehensive flood control program. By the end of 2016, flood control standard of urban sections of the basin has been basically improved to “once in 50 years” [11,12].

![Figure 1. Location, administrative division, elevation and water system of the study area.](image)

2.2. Data sets
The datasets we used include Digital Elevation model (DEM), remote-sensing images, distribution of rainfall stations and hydrological stations, rainfall, and flow etc. DEM data and two periods of remote-sensing data in 1985 and 2015 were obtained from Geospatial Data Cloud (http://www.gscloud.cn/). Additionally, rainfall stations, hydrological stations and corresponding ten flood events were acquired and analysed through China Hydrological Yearbook: Yellow River Basin.

3. Methods

3.1. SCS curve number model
Curve Number (CN) is a comprehensive non-dimensional parameter reflecting the characteristics of underlying surface, which can be used to express the underlying surface quantitatively. According to the five days’ total rainfall preceding the individual rainfall, the Antecedent Moisture Condition (AMC) of the entire watershed was classified into 3 grades (Ⅰ, Ⅱ, and Ⅲ) by SCS Curve Number Model. Meanwhile, with due considerations to the land use, soil type and other factors, the assignment
criteria of $CN$ value under AMC II condition ($CN_2$) was given out, then it can be converted into $CN_1$ and $CN_3$ according to the following formulas:

$$
CN_i = CN_2 - \frac{20 \times (100 - CN_2)}{100 - CN_2 + \exp[2.533 - 0.0636 \times (100 - CN_2)]}
$$

$$
CN_i = CN_2 \times \exp[0.0673 \times (100 - CN_2)]
$$

The elevation of the study area varies obviously, and the average slopes of the sub-basins are different. According to formula (2), $CN_2$ value was corrected by slope.

$$
CN_{2s} = \frac{CN_i - CN_2}{3}[1 - 2\exp(-13.86slp)] + CN_2
$$

Where $CN_{2s}$ is the number of curves under AMC II condition after slope correction, and $slp$ is the average slope of each sub-basin (%).

3.2. Hydrological model HEC-HMS

The Hydrologic Engineering Center’s Hydrological Model System (HEC-HMS), developed by the Hydrological Engineering Center of the United States Army Corps of Engineers, was chosen to simulate and calculate the rainfall-runoff in the study area. HEC-HMS includes basin module, control setup module, meteorological module and data input module. Similar to other considerable studies, evapotranspiration losses of the basin are negligible relative to runoff during storm-floods [13,14].

4. Construction of HEC-HMS

4.1. Data processing

4.1.1. DEM processing. Based on actual river system in the study area, firstly we utilized “DEM Reconditioning” command to modify the initial DEM data, and divided the drainage basin into 49 sub-basins on account of the setting of watershed outlet. Afterwards, HEC-HMS model for the entire basin was established based on hydrological analysis of DEM (figure 2).

![Figure 2. Basic document of HEC-HMS in the study area.](image)

4.1.2. Remote-sensing image processing. Referring to classification standards of land resources in China, the land use in the study area was classified into 5 types: arable land, construction land, forest land, water area and grass land. Additionally, land use maps of 1985 and 2015 in the study area were obtained by remote sensing interpretation software ENVI (figure 3).
4.1.3. Rainfall and flow data processing. There are 38 rainfall stations and 2 hydrological stations within the study area. Considering the integrity and accessibility of measured rainfall and flow data, we chose five flood processes 198006, 198206, 198307, 198407 and 198508 for the underlying surface condition in 1985, as well as five flood processes 201406, 201408, 201507, 201508 and 201607 for the underlying surface condition in 2015 (table 1).

**Table 1.** Statistics of 10 typical floods.

| Underlying surface condition | Flood number | Starting time | Ending time   | Average rainfall (mm) | Peak discharge (m³/s) |
|-----------------------------|--------------|---------------|---------------|-----------------------|----------------------|
| 1985                        | 198006       | 06-28T00:00   | 07-04T00:00   | 128.5                 | 182.0                |
| 198206                      |              | 06-16T00:00   | 06-20T08:00   | 44.3                  | 119.6                |
| 198307                      |              | 07-27T00:00   | 08-04T00:00   | 113.4                 | 130.5                |
| 198407                      |              | 07-13T05:00   | 07-19T12:00   | 104.5                 | 114.8                |
| 198508                      |              | 08-11T10:00   | 08-16T20:00   | 122.6                 | 177.8                |
| 2015                        | 201406       | 06-21T11:00   | 06-26T02:00   | 63.5                  | 164.3                |
| 201408                      |              | 08-05T10:00   | 08-11T05:00   | 55.4                  | 131.1                |
| 201507                      |              | 07-20T03:00   | 07-28T04:00   | 87.2                  | 264.2                |
| 201508                      |              | 08-11T10:00   | 08-20T08:00   | 65.4                  | 186.3                |
| 201607                      |              | 07-12T02:00   | 07-20T06:00   | 94.1                  | 164.1                |

The spatial distribution of rainfall in the watershed is extremely uneven according to the measured rainfall data. Therefore, the IDW (Inverse Distance Weighted) approach was applied to convert the measured rainfall events 198006, 198206 and 201607 into 198006-1, 198206-1 and 201607-1 whose spatial distribution was uniform, as the average rainfall stayed the same that was 128.5 mm, 44.3 mm and 94.1 mm respectively.

4.2. Model calibration and validation

Inputting the CN₂S values of two periods into the basic documents, we built up HEC-HMS model under the underlying surface conditions in 1985 and 2015 respectively. So as to quantitatively compare the simulated values with measured ones and guarantee validity of parameters, four evaluation indexes including the deviation of runoff volumes ($D_v$), the deviation of peak discharge ($D_p$), absolute error of time to peak ($\Delta T$), and the Nash-Sutcliffe coefficient of efficiency ($E$) were selected to constrain the model parameters (table 2). The equations for $D_v$, $D_p$, $\Delta T$, and $E$ are as follows:
\[
D_i(\%) = \frac{\sum_{i=1}^{N} Q_{op} - \sum_{i=1}^{N} Q_{sp}}{\sum_{i=1}^{N} Q_{op}} \times 100
\]
\[
D_s(\%) = \frac{Q_{op} - Q_{sp}}{Q_{op}} \times 100
\]
\[
\Delta T = T_{op} - T_{sp}
\]
\[
E = 1 - \frac{\sum_{i=1}^{N} (Q_{op} - Q_{sp})^2}{\sum_{i=1}^{N} (Q_{op} - \overline{Q})^2}
\]

where \(Q_{op}\), \(Q_{sp}\) are the observed and simulated flow at time step \(i\) (m³/s); \(Q_{op}, Q_{sp}\) are the peak discharges of observed and simulated hydrograph over the simulation period (m³/s); \(T_{op}, T_{sp}\) are the time of observed and simulated hydrograph peaks to arrive (h); \(\overline{Q}\) is the average observed flow over the simulation period (m³/s).

**Table 2.** Statistics of simulated evaluation indexes under the underlying surface conditions in 1985 and 2015.

| Underlying surface condition | Flood number | evaluation index | \(D_i(\%)\) | \(D_s(\%)\) | \(\Delta T(h)\) | \(E\) |
|------------------------------|--------------|------------------|------------|------------|-------------|-------|
| 1985                         | calibration period | 198006 | -9.72 | 0.43 | 0 | 0.892 |
|                              |               | 198206 | 2.66 | 9.78 | 1 | 0.913 |
|                              |               | 198307 | -2.67 | -2.76 | -2 | 0.935 |
|                              | mean absolute value |           | 5.02 | 4.32 | 1 | 0.913 |
|                              | validation period | 198407 | 6.43 | -3.45 | 0 | 0.916 |
|                              |               | 198508 | 7.67 | 5.43 | 2 | 0.887 |
|                              | mean absolute value |           | 7.05 | 4.44 | 1 | 0.902 |
| 2015                         | calibration period | 201406 | -6.46 | -5.54 | 2 | 0.884 |
|                              |               | 201408 | 5.28 | 4.46 | 2 | 0.912 |
|                              |               | 201507 | 5.21 | 4.04 | -1 | 0.945 |
|                              | mean absolute value |           | 5.65 | 4.68 | 2 | 0.914 |
|                              | validation period | 201508 | -5.34 | 4.65 | -1 | 0.921 |
|                              |               | 201607 | 6.58 | -5.32 | 1 | 0.871 |
|                              | mean absolute value |           | 5.96 | 4.99 | 1 | 0.896 |

Note: A negative value of \(\Delta T\) means that appearing time of peak discharge advances; Otherwise, a positive value of \(\Delta T\) means that appearing time of peak discharge lags.

Generally speaking, all calibration and validation results of constructed HEC-HMS model under the underlying surface conditions in 1985 and 2015 are satisfying overall. It is clear that the calibrated HEC-HMS model well simulate the runoff processes, and it can be used to evaluate the influence of underlying surface changes on the runoff generation under various underlying surface conditions and rainfall events with reliable quality in the study area.

5. Results and discussion

5.1. Changes of the land-use types and CN2S values of sub-basins

Land use in the study area changed dramatically from 1985 to 2015 (figure 4). Since 1985, the area of construction land, water and forest land have increased to varying degrees, of which the construction land has increased from 1138 km² to 2491 km² with a growth rate of 119%. At the same time, the arable land and grassland area have reduced to varying degrees.

The \(\text{CN}_{2S}\) value of each sub-basin also changed greatly (figure 5), change rate of which ranged from -8.51% to 33.42%. Sub-basins with negative growth of \(\text{CN}_{2S}\) value located along the Xiaoping River. These areas have been comprehensively improved and developed into Wetland parks. There were 28 sub-basins with the growth rate of \(\text{CN}_{2S}\) value ranging from 0 to 5%. At the same time, the sub-basins with the growth rate of \(\text{CN}_{2S}\) value greater than 5% were mainly concentrated in Jinan and

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IOP Conf. Series: Earth and Environmental Science 344 (2019) 012117 doi:10.1088/1755-1315/344/1/012117
Zibo city or in the central part of Zouping and Zhangqiu, which was the inevitable result of the increase of construction land derived from urbanization.

Figure 4. Comparison of land use between 1985 and 2015 in the study area.

Figure 5. Distribution of change rate of $CN_{2S}$ value of the sub-basins in the study area.

5.2. Impact of underlying surface changes on flood characteristics

On the basis of the simulated rainfall-runoff results of the above selected 10 particular rainfall events under different underlying surface conditions, the quantifiable effects of underlying surface changes on flood characteristics in the past 30 years in the study area can be obtained: (1) Except that the peak discharge of 198206 rainfall decreased slightly, others all increased by 9.8%~36.2%, with an average growth rate of 15.4%; (2) All flood volume of the 10 rainfall events increased, ranging from 1.1% to 42.4%, and the average growth rate was 17.8%; (3) The time for flood peaks of the 10 rainfall events were all in advance unevenly by an average of 7 hours.

In general, before 1985, urbanization had not taken place on a large scale in the study area, and the detention capacity of the basin was relatively strong. After large-scale urbanization, the proportion of land use types changed, and the proportion of impervious area and $CN_{2S}$ value increased, which resulted that flood volume and peak discharge increased and the time for peak advanced under the same rainfall conditions.

5.3. Effect of underlying surface changes on runoff response characteristics of sub-basins

Transferring the rainfall data of 198006-1, 198206-1 and 201607-1 with uniform spatial distribution into HEC-HMS model, scatter diagram of runoff variation values $\Delta R$ and $\Delta CN_{2S}$ of the sub-basins was illustrated (figure 6). According to figure 6, there was a linear positive correlation between $\Delta R$ and $\Delta CN_{2S}$ in the sub-basins for the rainfall whose spatial distribution was even. The general trend lines between $\Delta R$ and $\Delta CN_{2S}$ of three rainfall events are as follows, respectively: $\Delta R=0.74\Delta CN_{2S}$, $\Delta R=0.25\Delta CN_{2S}$, $\Delta R=0.52\Delta CN_{2S}$. Irrespective of influence of rainfall, the relationship between $\Delta R$ and
$\Delta CN_{2S}$ is $\frac{\Delta R}{P \Delta CN_{2S}} = 0.0058$. That is to say, the runoff $R$ increases by 0.0058 mm for each unit increase of $CN_{2S}$ value under the unit rainfall.

**Figure 6.** Scatter plot of relationship of $\Delta R \sim \Delta CN_{2S}$ of different rainfall in sub-basins. (a) 198006-1, $P=128.5$ mm, (b) 198206-1, $P=44.3$ mm and (c) 201607-1, $P=94.1$ mm.

### 6. Conclusions
From 1985 to 2015, the underlying surface of Xiaoqing River basin changed greatly owing to the large-scale urbanization, which resulted in variations of the hydrological characteristics in the whole basin. Especially after the “7.18” flood hazard, the government reinforced the comprehensive management of flood control and drainage across the basin, and relevant researches became more and more abundant. We adopted SCS Curve Number approach to quantitatively evaluate the underlying surface conditions and its changes, and chose HEC-HMS model to simulate and calculate the runoff yield and confluence of different rainfalls under the two underlying surface conditions. Additionally, the influence of underlying surface changes on flood characteristics was analysed and the quantitative relationship between rainfall, runoff and underlying surface change was obtained. The main conclusions are as follows:

- The study area is divided into 49 sub-basins, and the average growth rate of $CN_{2S}$ is 5.08%. The $CN_{2S}$ value of 41 sub-basins increased by 0.84%~33.42%, and the sub-basins, of which the $CN_{2S}$ values increased by more than 5%, were mainly concentrated in Jinan and Zibo urban areas.
- According to the simulation results of 10 rainfall events under the underlying surface condition in 1985 and 2015, the underlying surface condition in 2015 is easier to produce runoff than that in 1985. The results indicated that influence of increased urbanization in 2015 increased in the flood volume and the peak discharge by approximately 17.8% and 15.4% on average respectively. Also the time to peak advanced by 7 hours.
- There was a linear positive correlation between $\Delta R$ and $\Delta CN_{2S}$. Relationship among $P$, $\Delta R$, and $\Delta CN_{2S}$ is $\frac{\Delta R}{P \Delta CN_{2S}} = 0.0058$, indicating the $R$ increases by 0.0058 mm for every unit increase of $CN_{2S}$ value under unit rainfall.

### Acknowledgments
This research is supported by the Open Research Fund of State key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (2017491911) and the Science and Technology Project of Zhejiang Water Conservancy Department (RC1804).
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