Investigation of impact of land use changes in watershed on surface runoff

Abstract

Rapid urbanization can greatly affect the watershed land cover/land use and surface runoff. It is important to appropriately utilize the hydrologic model to estimate surface runoff to plan the water conservation measures and reduce the flooding disasters induced by urbanization. For urbanized cities having few field observed or/and experimental runoff data, the Soil Conservation Service Curve Number (SCS-CN) model integrating with GIS offers the best option to evaluate the surface runoff, runoff depth and coefficient in the watershed affected by urbanization. This study shows that rapid urbanization has significant effect on watershed land use and its surface runoff. Simulations demonstrate that monthly peak runoff depths during rapid urbanization period are higher than pre-rapid urbanization period. The runoff changes due to land use or rainfall change are investigated using SCS-CN Model. The results demonstrate that for the same rainfall events over the same catchment with and without urbanization, the urbanized one has much larger annual runoff depth and volume than the one without urbanization. It is revealed that the watershed land use is one of the important factors affecting surface runoff. This study is expected to advance our understanding of the urban flood measures and watershed environment protection.

Keywords: land use types, surface runoff, urbanization, SCS-CN model, precipitation

Introduction

Urbanization is growing rapidly at a global scale. China is a typical example which has been undergone urbanization at an unprecedented rate since 1978. Studies show that China’s urbanization rate increased from 13.6% in 1980 to 52.6% in 2012 and it will maintain to be one of the most important driving forces for China’s future economic growth. The rapid urban development, however, has significantly affected (mostly adversely) the natural hydrologic systems in and around cities. For example, urbanization usually leads to an increase of construction land and decrease of agricultural land and water areas. Comparing with the natural watershed geomorphologic area, the impervious surfaces generate larger volume of surface runoff and thus leads to more flood events. With the rapid urbanization development, many cities in China have been suffering from frequent flooding, especially waterlog. This also takes place globally. For example, many major urban areas in the United States also suffer from recurring sewer overflow events due to the excess discharge of stormwater to water bodies. As such, the hydrological problems induced by rapid urbanization have attracted greater attention of hydrologists and researchers working in this area. In particular, the surface runoff generated by rainfall in a watershed is one of the most important parameters in designing the sustainable hydraulic structures and flooding control measures. Therefore, quantification of the impacts of geomorphological changes of watershed on the surface runoff is crucial in terms of preventing urban flooding, reducing economic loss and protecting human beings. Due to its practical importance, many studies have been carried out in past decades. So far, some hydrological models have been developed and widely used to assess the impact of changes of watershed geomorphological features on the formation of the surface runoff. Investigated the changes of surface runoff peaks induced by urbanization using the long-term field data. The effect of land cover changes on the surface runoff in Rhine basin was modeled by Hundecha et al. who applied the modified semi-distributed conceptual model. The MIKE SHE model was used by Vansteenkiste et al. to simulate the catchment runoff and the extreme flow. Sherif investigated rainfall–runoff process for the whole Egypt using the Soil Conservation Service Curve Number (SCS-CN) method integrated with remote sensing and Geographic Information System (GIS). Recently, Fernández-Pato et al. used the two-dimensional (2D) shallow water equations to simulate the surface flow and runoff induced by topography and/or rainfall. Although many hydrologic models are available for estimating the surface runoff and storm rain water quality management, their application are limited due to their requirements of large data and physical parameters and complicated calibration process. For example, the Qiantang Estuary in China, a famous estuary in the world due to its macro tidal, has been significantly affected by human activities. As a result, flood disasters and storm tides/surges have greatly increased in recent decades. However, the observed surface runoff data in this area are scarce and the relevant experimental data are also limited due to its complicated macro tidal flow structure. In this situation, it is important to select appropriate hydrologic model for estimating the rainfall induced surface runoff within the watershed. Such information is important in order to predict the responses to the land use changes induced by urban development. Ultimately, this will be able to provide important information for planning of water conservation measures and reducing the local flooding hazards. To this end, the SCS-CN model, originally developed by the USDA-Soil Conservation Service in 1972, is perhaps the best option for estimating the surface runoff in this study. The SCS-CN model requires few data of the catchment, which is the situation of the catchment in this study, and clearly and reasonably describes the assumptions of the major catchment processes.
parameter, the CN values can be determined for various antecedent moisture content conditions\textsuperscript{22,28} and thus has wide application. Since its development, the model has been widely applied to predict the rainfall-runoff process\textsuperscript{15,29–31} and has been referred as “blue collar” hydrology\textsuperscript{32}, verifying the suitability of the model in this study. This study aims at quantifying the impacts of urbanization and river networks changes on the surface runoff and attempting to develop a decision support measures for urban development. The significant hydrologic parameters obtained will be useful for urban flood control and watershed environment protection. The Qiantang Estuary is chosen as a case study because the urbanization around the Qiantang Estuary has been rapidly developed since the middle of 1980s. This study will compare the runoff change between 1975-1986 and 1987-2010 in order to demonstrate the response of the surface runoff to land use changes as a result of urbanization. The main objectives of this study are:

1. To assess the geomorphic features changes of the catchments (the Qiantang Estuary) caused by urbanization;
2. To investigate the influence of land cover changes on surface runoff in watershed from 1975 to 2010, and
3. To estimate the potential runoff volume, runoff depth and runoff coefficient. It is anticipated that this study will provide some valuable important information and simulated data on the flood control measures and water environment protection around the urbanized city.

Study area and data

This study is carried out on a representative part of the Qiantang Estuary, located upstream of the Hangzhou city, the capital city of Zhejiang Province in the East of China (Figure 1). The study area mainly consists of the Fuchun River and its two sub-catchments, namely Fuyang and Tonglu catchments. The long-term average annual precipitation in this area is about 1510mm and the rainfall from April to October often accounts for 72\% of the total annual precipitation with the most of the highest intensity storms taking place in June\textsuperscript{32,34}. Main data sources include land use map and the river network obtained from the Bureau of Surveying and Mapping of Zhejiang Province.\textsuperscript{35,36} Soil group data are obtained from the Qiantang River Record\textsuperscript{37} and Water Conservancy Records of Fuyang.\textsuperscript{38} Long-term monthly precipitation data were measured at 13 rainfall stations, which were appropriately designed in the catchment, during the period of 1975 to 2010 (Hydrology Bureau of Zhejiang Province (HBZP),\textsuperscript{39} covering the Fuchun River and all of its tributaries, as shown in Figure 1.

Methodology

The SCS-CN model

The SCS-CN model, used to estimate the surface runoff in this study, is developed by the United States Soil Conservation Service in 1972.\textsuperscript{26} The SCS-CN method builds on empirical studies and only calculates the direct surface runoff. It does not consider the runoff caused by high groundwater levels.\textsuperscript{22,28} (Since its development, the model has been widely used for runoff estimation, water resource management and storm water modeling.\textsuperscript{11,29–31} Some related study was conducted by Qin et al.\textsuperscript{39} who applied the SCS-CN model for predicting the direct runoff from rainfall in Linan watershed, which is close to the location of this study. Xiao et al.\textsuperscript{21} employed the standard SCS-CN model to estimate the runoff in the Liudaoqou watershed. These studies demonstrate that the SCS-CN model is capable of estimating the surface runoff with satisfactory accuracy. Though the details of the SCS-CN model can be found in USDA SCS,\textsuperscript{28} we provide a brief description of the model for completeness and convenience. The model assumes that the runoff ($Q$) is proportional to the precipitation ($P$). The relationship of $Q$ and $P$, after some simplifying assumptions, can be written as following:\textsuperscript{26}

$$ Q = P - I_a = F + Q $$ \hspace{1cm} (1)

$$ Q = \frac{P - I_a}{P} = \frac{F}{S} $$ \hspace{1cm} (2)

Where $Q$ is runoff depth (mm), $P$ is precipitation (mm), $F$ is cumulative infiltration (mm), $I_a$ is the initial abstraction and can be calculated as $I_a = \lambda S$, where $\lambda$ is mainly influenced by the geography and weather. In general, the value of $\lambda$ can be taken as 0.2.\textsuperscript{21,40} Using the relation of the precipitation and the initial abstraction, the SCS-CN model can be expressed as following:\textsuperscript{26,41}

$$ Q = \left(\frac{P - 0.2S}{P + 0.8S}\right)^2, \text{ for } P \geq I_a $$ \hspace{1cm} (3a)

$$ Q = 0, \text{ for } P < I_a $$ \hspace{1cm} (3b)

For convenience and standardization application of Eq. (3), parameter $S$ in (3) can be expressed as:\textsuperscript{26,41}

$$ S = \frac{25400}{CN - 254} $$ \hspace{1cm} (4)

Where $CN$ is the runoff curve number, which depends on land cover, soil groups and soil antecedent moisture condition (AMC) Equation (3) shows that if the precipitation $P$ and parameter $S$ (or $CN$ value) are known, the surface runoff can be evaluated.

Determination of the hydrological parameters in the model

Determination of average precipitation ($P$): Although precipitation statistic data can be obtained from the rainfall hydrological stations, they usually distribute irregularly in the study area. Therefore, the average precipitation ($P$) in the study area is calculated using these data. To this end, Thiessen polygons method,\textsuperscript{42,43} which is based on the long-term mean monthly rainfall data, is used to estimate the average precipitation. The results calculated from 13 rainfall hydrological stations from 1975 to 2010 are shown in Figure 2.

Determination of CN value: The runoff curve number ($CN$) is an empirical parameter used in hydrology for directly predicting the...
surface runoff generated from rainfall. It is based on the catchment’s types of watershed geomorphology, hydrologic soil group and hydrologic condition. SCS-CN method considers three antecedent moisture condition (AMC) to indicate the extent of soil saturation, namely Dry (AMCI); Moderate (AMCII) and Wet (AMC III). Among them, Moderate (AMCII) stands for the normal or average soil moisture condition. The soil groups have been classified into four categories, A, B, C and D by SCS based on the study of the permeability over 4000 soil samples in the United States. Group A soils are coarse and sandy, with the highest rate of infiltration and the lowest potential runoff. Group D soils, on the contrast, are heavy, clayey and poorly drained with the lowest rate of infiltration and the highest potential for the surface runoff. Group B and C soils are intermediate between groups A and D. In the SCS model, the CN values for types of land cover and group soils for AMCII conditions were determined by USDA-Soil Conservation Service, called CN value table. In general, the CN value increases with the increase of the moisture of the soil. The range of CN values is from 0 to 100.

Figure 2 Average monthly precipitation at the study area (A) 1975 to 1985; (B) 1986 to 2010.

To ensure the simulation accuracy, the CN value should be determined according to the land cover/land use and group soils in the study watershed which may be quite different from those in US. In this study, the land use of watershed is classified into seven types, namely water area, arable land, forest land, built-area, plant area (economic plants), grass land and other land. The distribution of the different geomorphologies in the study area in 1978 and 2010 is shown in Figure 3(A) & Figure 3(B), respectively. Figure 3(A) is obtained using the topographic maps in 1978 while Figure 3(B) is obtained using the satellite image in 2010. The land use data in the study area in 1978 and 2010 are then obtained by manually digitizing the maps and data. The results are listed in Table 1. The Qiantang River Record and Water Conservancy Records of Fuyang show that the total antecedent moisture condition of soils in the study area is normal. The soil groups consist of the red loam, relative to “C” groups; paddy soil; wet soil and built land. The red loam, which is about 69.25% of the total area in the Fuchun river catchment, mainly locates at the forest region at the altitude from 200 to 500 meter. Paddy soil type whose hydrologic soil group is equivalent to that of group “B” accounts for about 17.29% of the total area and lies in the plain and low hilly region Paddy soil area mainly includes the arable land and the economic plants. Other soil types are wet soil and built land and account for about 13.46% of the total area and have the lowest infiltration rate and the highest runoff. Those data will be used to estimate the CN value for different geomorphologic features and soil groups in the study area. The procedure for evaluating the CN value in the study area is as following:

Figure 3 Types of land use in the study area (A) 1978; (B) 2010.
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1. Assume a group of CN values in the study area based on its land types, hydrologic soil group\textsuperscript{26,28} and referred to the USDA’S SCS CN values.\textsuperscript{29,30}  
2. Apply SCS-CN model programmed by Matlab and use the assumed CN values to simulate the average monthly runoff using the rainfall and land data of the period 1975-1985. Calculate the average annual runoff depth.  
3. Compare the calculated and measured average annual runoff depth during the period of 1975-1985. If the error is within the prescribed accuracy (2% in this study), the CN values are correct in the study area. Otherwise, modifying the CN values and repeating step (2) until the prescribed simulation accuracy is achieved.  

In this study, the final CN values are obtained after 10 iterations.  
The results are listed in Table 2. These CN values are used to calculate the surface runoff in the study area during the period 1975-1985 and 1986-2010.

Table 1 Variation of the land use of watershed in the study area during 1978 to 2010

<table>
<thead>
<tr>
<th>Type of land use</th>
<th>1978 Area (km(^2))</th>
<th>Percentage (%)</th>
<th>2010 Area (km(^2))</th>
<th>Percentage (%)</th>
<th>the % of change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water area</td>
<td>170.55</td>
<td>4.46</td>
<td>131.24</td>
<td>3.43</td>
<td>-23.09</td>
</tr>
<tr>
<td>Forest land</td>
<td>2651.87</td>
<td>69.30</td>
<td>2564.26</td>
<td>67.01</td>
<td>-33.04</td>
</tr>
<tr>
<td>Arable land</td>
<td>656.52</td>
<td>17.16</td>
<td>463.63</td>
<td>12.12</td>
<td>-29.37</td>
</tr>
<tr>
<td>Plant area</td>
<td>130.56</td>
<td>3.41</td>
<td>150.14</td>
<td>3.92</td>
<td>14.96</td>
</tr>
<tr>
<td>Built land</td>
<td>81.74</td>
<td>2.13</td>
<td>359.1</td>
<td>9.38</td>
<td>340.38</td>
</tr>
<tr>
<td>Grass land</td>
<td>73.91</td>
<td>1.93</td>
<td>85.83</td>
<td>2.24</td>
<td>16.06</td>
</tr>
<tr>
<td>Other land</td>
<td>61.36</td>
<td>1.60</td>
<td>72.29</td>
<td>1.89</td>
<td>18.13</td>
</tr>
<tr>
<td>Total</td>
<td>3826.50</td>
<td>100</td>
<td>3826.50</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 The values of CN in the study area

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Water area</th>
<th>Frost land</th>
<th>Arable land</th>
<th>Plant land</th>
<th>Built land</th>
<th>Grass land</th>
<th>Other land</th>
<th>CN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>70</td>
<td>81</td>
<td>55</td>
<td>92</td>
<td>65</td>
<td>82</td>
<td></td>
</tr>
</tbody>
</table>

Results and discussion

Validation of the model

The CN values determined by comparing the calculated and measured average annual runoff depth during the period of 1975-1985 are validated using the measured average annual runoff depth during 1986-2000. The measured average annual runoff depth in the period of 1986-2000 is 790.93mm, which is slightly lower than the calculated average annual runoff depth of 804.49 mm (relative error is 1.17%). This good agreement between the simulation and the field measurement of the average annual runoff depth demonstrates that SCS-CN model can be applied to estimate the effect of the urbanization on the surface runoff in the study area.

Impact of urbanization on the watershed land cover

Rapid expansion of urban areas around the Qiantang Estuary has greatly altered the original land cover/land use of watershed in the region.\textsuperscript{31} For example, Table 1 shows that the arable area has been significantly reduced from 17.16% of the total land area in 1978 to 12.12% in 2010. A slight decrease of water and forest areas is also seen in Table 1. On the contrary, the built land has dramatically increased from 2.13% in 1978 to 9.38% in 2010, an increase of 440% within three decades due to the rapid urbanization. Surface runoff is formed when the rainfall intensity exceeds the soil infiltration rate and surpasses the water retention capacity on the land surface\textsuperscript{32} and is affected by the geomorphology surface in the catchment.\textsuperscript{33} The geomorphology surface in the catchment can be greatly modified during the process of urbanization (Table 1); which in turn can significantly alter the hydrologic processes of the infiltration and the surface runoff in the catchment.\textsuperscript{34} Therefore, the changes of the watershed geomorphologic features in the study catchment due to the rapid and dramatic urbanization will greatly affect the rainfall–runoff relationship, as demonstrated below.

Effect of the watershed land use changes on surface runoff

Change of surface runoff: To calculate the surface runoff depth, values of parameters of P, CN and percentage of different land types are input to the verified SCS-CN model programmed by using Matlab. The average monthly runoff depths before and after urbanization are then calculated and plotted in Figure 4 for the period of 1975-1985 (Figure 4A) and 1986-2010 (Figure 4B), respectively. Comparing (Figure 4A) (Figure 4B) reveals that the monthly peak runoff depths during the period of 1986-2010 are, in general, larger than those during the period of 1975-1985. In particular, the highest monthly peak runoff in the period of 1986-2010 is about 1.38 times of the highest monthly peak runoff in the period of 1975-1985, demonstrating the great effect of the intense urbanization on the surface runoff in the study area. Using the simulated average monthly runoff, the average annual runoff depth can be calculated in the study area for two periods investigated. The calculated results show that the average annual runoff depth for the period 1986-2010 is 747.9 mm while the average annual runoff depth for the period 1975-1985 is 712.0 mm, an increase of 35.9 mm (or 5%). This runoff increase causes the increase of total annual runoff

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To analyze the change in runoff due to the land use change, the SCS-CN is run to evaluate the sole effect of urbanization on the surface runoff in the study area. To this end, the same rainfall series (during the period of 1986-2010) in the study catchment is used with the built land increasing from 2.13% in 1978 to 9.38% in 2010. The result shows that the increase of the built land causes the increase of the annual runoff depth by 15.71 mm in the study area, which is about 43.5% of the total increase of the annual runoff depth in the study area. This demonstrates that the land use of watersheds is the most important factor affecting the surface runoff in the study area. Furthermore, SCS-CN model is run to investigate the effect of the rainfall change on the surface runoff from the period of 1975-1985 to 1986-2010 for the same land cover in 1978 in the study area, a possible evaluation of the climate change on the surface runoff (thus, the urban flooding). The simulated results show that the annual runoff depth during the period of 1986-2010 is 20.14 mm greater than that during the period of 1975-1985 due to the rainfall change, which shows that the rainfall change is another vital factor affecting the surface runoff.

Comparison of change of surface runoff between two subcatchments: In order to illustrate the runoff variation at different subcatchments caused by land use change in watershed, the study area is divided into two subcatchments, namely Tonglu and Fuyang with areas of 1373.78 km$^2$ and 2452.72 km$^2$ respectively. The division is mainly based on the river system, the distribution of hydrological stations and the built land of Tonglu and Fuyang Districts (Figure 5). These two subcatchments are selected because their urbanization rate is very different with the built-land in Fuyang being much higher than that in Tonglu (see below). SCS-CN model is applied to estimate the average annual runoff depth and coefficient in two subareas, using the same model parameters, P and CN and land types. The results are listed in Table 3 which shows that the annual runoff depth and coefficient in both subcatchments have increased after urbanization. It is noted that although the two subcatchments have similar increase of the runoff coefficient over the period investigated; the increase of the runoff depth in Fuyang area is much higher than that in Tonglu area; which reflects the effect of the changes of watershed land use on surface runoff. It is known that larger urban areas increases the impervious surface area, leading to larger surface runoff. In this study, the increase of the built-land in Fuyang catchment from 1978 to 2010 is 8.55%, while such increase in Tonglu catchment over the same period is only 4.92%. Consequently, the increase of the runoff depth in Fuyang catchment is larger than that in Tonglu catchment, as expected.

Conclusion

Surface runoff of a watershed can be estimated using the numerical modeling simulation or/and obtained through field measurements. Many numerical models require sufficient lab/field measured data for their validation before they can be confidently used to evaluate the surface runoff of a watershed. For the catchment having few observed runoff data, the Soil Conservation Service Curve Number (SCS-CN) model, developed by USDA, offers the best option for simulating the surface runoff in the catchment as the model requires less observed data. This is the main reason that the SCS-CN model is applied to evaluate the effect of the urbanization induced land use change on urban surface runoff in the Qiantang Estuary area where few relevant field data are available. The model parameters are determined using
the long-term hydrologic observed data, land cover types and soil groups in the study watershed. The SCS-CN model, integrated with GIS, is firstly validated using the measured average annual runoff depth in the period of 1986-2000. A good agreement is obtained between the simulated and measured annual runoff depth with the relative error being 1.15%, indicating that the model has satisfactory simulation accuracy. The validated SCS-CN model is then applied to simulate the surface runoff, runoff depth and runoff coefficient in this study watershed before and after urbanization. The simulation shows that the urbanization causes significantly negative impacts on watershed geomorphologic features/land use types and greatly increases the surface runoff. In general, the areas of arable land, water body and forest land decrease, primarily due to urbanization, while built land has been significantly increased. Simulated results demonstrate that the average annual runoff depth has increased by 35.85mm after urbanization, which is equivalent to the increase of $1.37 \times 10^3$ m$^3$ annual runoff volume in the study area. In particular, the monthly highest peak runoff in the period of 1986-2010 is about 1.38 times of that in the period of 1975-1985, implying that the likelihood of flood is increased after the rapid urbanization. The study agrees well with the events of flood disasters in the Qiantang Estuary in past decades. The impact of changes of land cover on the surface runoff in Tonglu (upstream) and Fuyang (downstream) subcatchments has been investigated. The results show that the surface runoff has a distinct response to the changes of land use of watershed. The effects of urbanization or rainfall change on runoff change are investigated. Simulated results indicate that under the same condition of rainfall over the same catchment before and after urbanization, the one after urbanization has much larger annual runoff depth and volume than the one pre-urbanization. Study also shows that the rainfall change, primarily due to the climate change, also plays an important role in generating the surface runoff. Therefore, it is desirable to adapt to the systematical approach and compensation measures in order to mitigate the negative impact of the urban developments on the surface runoff and local flooding. This may be achieved by combining the vegetative structures and permeable paving materials with subsurface infiltration beds, green roof substrate, and protection of watershed geomorphologic features/land use types. Furthermore, there is also a need to build appropriate detention structures to temporarily store rainwater to reduce pluvial flooding during intense rainstorms as well as to use the stored rainwater as a resource, such as landscape irrigation and household water use. Some important hydrologic parameters obtained from this study, such as runoff volume, runoff depth, runoff coefficient and CN values, will be very useful for future flood control and hydrological structure design in the study area. The method of this study may also be worth of referring to other similar watersheds.

### Table 3 Runoff change in Tonglu (upstream) and Fuyang (downstream) catchments pre and post urbanization

<table>
<thead>
<tr>
<th>Modeled period</th>
<th>Tonglu catchment</th>
<th>Fuyang catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average annual runoff depth (mm)</td>
<td>Average annual runoff coefficient</td>
</tr>
<tr>
<td>1975-1985</td>
<td>716.80</td>
<td>0.485</td>
</tr>
<tr>
<td>1986-2010</td>
<td>729.46</td>
<td>0.503</td>
</tr>
<tr>
<td>Change</td>
<td>1.77%</td>
<td>3.71%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.44%</td>
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<tr>
<td></td>
<td></td>
<td>4.03%</td>
</tr>
</tbody>
</table>

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### Conflict of interests

The authors declare no conflict of interest.

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