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Assessing the Effect of Land Use Change on Surface Runoff in a Rapidly Urbanized City: A Case Study of the Central Area of Beijing

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Abstract: The change in land use during the process of urbanization affects surface runoff and increases flood risk in big cities. This study investigated the impact of land use change on surface runoff in Beijing's central area during the period of rapid urbanization from 1984 to 2019. Land use maps of 1984, 1999, 2009, and 2019 were generated by image classification of Landsat images. Surface runoffs were calculated with the Soil Conservation Service curve number (SCS-CN) model. Correlation analysis was used to identify the dominant factor of land use change affecting surface runoff. The result showed that the variation trend of surface runoff was consistent with the trend of impervious land in Beijing's central area, which increased during 1984~2009 and decreased during 2009~2019. Correlation analysis showed that changes in surface runoff were most strongly correlated with changes in impervious surfaces when compared with the correlation of runoff with other types of land use. The results of this study may provide a reference for city flood control and urban planning in fast growing cities worldwide, especially in developing countries.

Keywords: land use change; urbanization; SCS-CN model; surface runoff; Beijing

1. Introduction

Urbanization is the inevitable trend of the development of the world today. It has been estimated that about 64% of developing countries and 86% of developed countries will be urbanized by 2050 [1,2]. In the process of urbanization, large amounts of agricultural or other non-urban land are transformed into impervious land and the land use change totally alters natural hydrological processes [3,4]. Several studies investigated the effects of urbanization-induced land use changes on runoff. The rapid expansion of urban impervious area increased surface runoff yield amount [5,6], peak discharge [7,8], and runoff ratio [9,10], reduced runoff response time [11,12], and changed hydrological regimes [12–14]. It also changed the long-term groundwater recharge [15,16] and water balance [17,18]. Quantitative assessment of the impact of urbanization on surface runoff is essential for urban planning, water resources management, and for early flood warning in big cities.

China has experienced rapid urbanization in the last 40 years and floods caused by rapid urbanization have threatened human health and economic development. A great deal of research on urban hydrological processes has been carried out in Shanghai [19], Shenzhen [20,21], Shenyang [22], Nanjing [23], and other cities. As the capital and supercity of China, urban flood and waterlogging in Beijing deserve special attention. Xu et al. [24] evaluated the impact of urbanization on rainfall-runoff

processes using the Storm Water Management Model (SWMM) in the Dahongmen catchment in Beijing and the results showed that the volume of surface runoff after urbanization was 3.5-times greater than that before urbanization, where the coefficient of runoff changed from 0.12 to 0.41. Fang et al. [25] used historical data to identify the impact of urbanization on typical rainfall-runoff process in the Liangshui River urban watershed and the results indicated that the runoff coefficient in the lower reaches was one-third of that in the upper reaches and pointed out that the proportion of impermeable area was the key control condition of the flood process.

Several approaches have been used to estimate the urban hydrological effect [26], including hydrological simulation, field experiments, and monitoring data comparison for different underlying surfaces. However, due to the high cost and restrictions imposed by urban management, it is difficult to acquire sufficient monitoring data. Modeling of social-ecological processes offer a possible avenue to deal with these challenges. The social-ecological model provides a process-based understanding of the complex linkages between people and the environment [27–29] and has been used by hydrologists for understanding the interaction of human society and hydrological systems. When coupled with land use data, models, such as SCS-CN, Soil and Water Assessment Tool (SWAT), SWMM, The Hydrologic Engineering Center's-Hydrologic Modeling System (HEC-HMS), and MIKE System Hydrological European (Mike SHE), have been extensively used to assess the effects of land use changes (predominantly urbanization) on hydrologic processes [30–34]. For example, Du et al. [35] coupled a distributed hydrologic and a dynamic land use change model to examine the effects of urbanization on annual runoff and flood events of the Qinhuai River watershed in China. Therefore, the applicability of the hydrological model for the assessment of land use change impact is cost-effective and efficient.

In this study, we selected the inner area within the Fifth Ring Road of Beijing, the core of the rapidly urbanized city, as the study case. We integrated GIS and remote sensing methods with the SCS-CN model to assess the impact of land use change on surface runoff. The main objectives were to: (1) investigate the characteristics of land use change from 1984 to 2019, (2) evaluate the impact of land use change on the temporal and spatial distribution of surface runoff, and (3) identify the main factors affecting surface runoff change.

2. Materials and Methods

2.1. Study Area

In this research, the area within the Fifth Ring Road of Beijing was chosen as the study area (39°26'–41°03'N, 115°25'–117°30'E). It occupies a total of 675 km² and belongs to the plain area with an average elevation of 48 m (Figure 1). The study area lies in the temperate monsoon climate region. The annual average precipitation is 548 mm, over 80% of which falls in the flood season (from June to September) [9]. The maximum daily precipitation from 1954 to 2011 in Beijing is shown in Figure 2a. The soil type in the study area is alluvial soil [36], the main soil texture is loam [37], and the average soil hydraulic conductivity in most areas of Beijing is 18–180 mm/h [38].

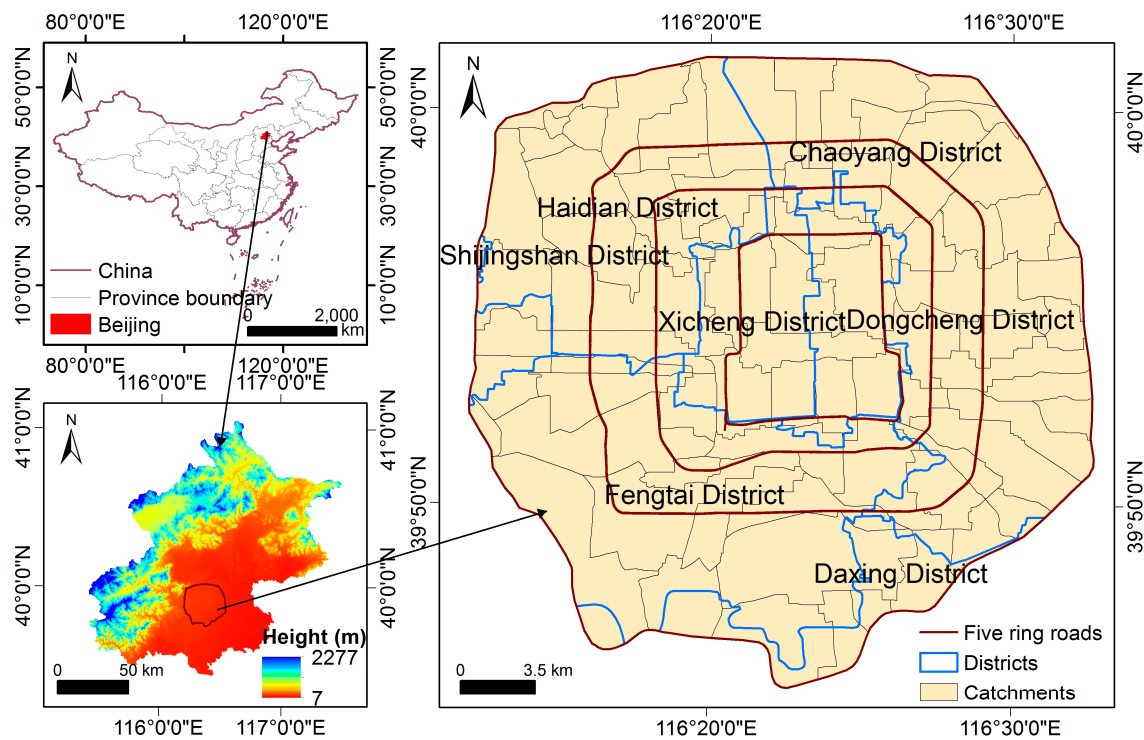


Figure 1. Location of the study area and the distribution of catchments in study area.

The urban area of Beijing has gradually expanded from the central to suburban areas and a ring road network was created in the past 30 years. The area within the Fifth Ring Road is the fastest growing urbanized section with most of the population and the greatest built-up areas. The change in land use has an obvious influence on runoff (Figure 2b). Therefore, it is essential and valuable to assess the hydrologic impacts of land use changes in the process of urbanization.

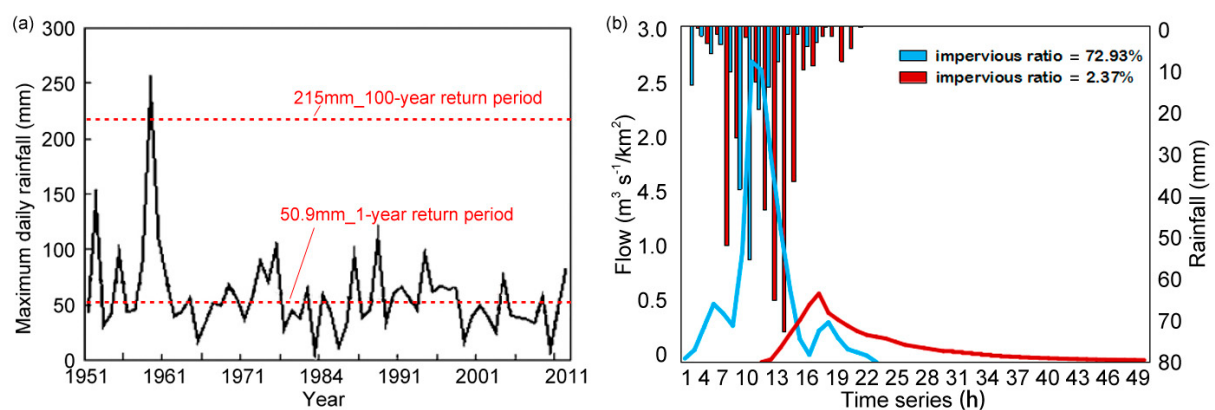


Figure 2. Characteristics of (a) maximum daily rainfall in July in Beijing and (b) hydrographs of river runoff with different degrees of urbanization.

2.2. Data Sources

The data used in this study were derived from three sources:

- (1) The Landsat Thematic Mapper (TM) and Operational Land Imager (OLI) remote sensing images of 1984, 1999, 2009, and 2019 were acquired from United States Geological Survey (USGS). The imaging dates for them were 16/08/1984, 01/07/1999, 22/09/2009, and 29/05/2019, respectively [39]. The spatial resolution of the image data is 30 m. These images were used to extract land use information;

- (2) Daily precipitation data series at 55 gauges in the urban area of Beijing were provided by the Beijing Meteorological Service [40];
- (3) The 1:450,000 map of the small watershed of Beijing was provided by Beijing Hydrological Station. The delineation of the catchments was carried out by combining multi-source data: the 1:10,000 Digital Elevation Model (DEM), the urban drainage pipelines data, sewage outlets, and water dams locations [41]. In this paper, the study area was divided into 77 catchments for surface runoff simulation.

2.3. Methods

2.3.1. Land Use Mapping and Change Analysis

The study area was classified into six types of land use: impervious land, water, unused land, woodland, grassland, and farmland. Detailed descriptions of these land use classes are provided in Table 1. The land use was mapped by support vector machine (SVM) classification method and manual post-editing. The training samples were manually selected from remote sensing images. The accuracy assessment points were generated randomly using ArcGIS and the ground truth classes for these points were manually identified using aerial photos and high-resolution images from Google Earth. The test sample size was 150 for each year.

Table 1. Land use classes and description used in this research.

Land Use	Description
Farmland	Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton. Crop vegetation accounts for greater than 30% of total vegetation. This class also includes all land being actively tilled.
Woodland	Areas dominated by trees and shrubs, which generally account for more than 30% percent of total cover.
Grassland	Areas dominated by herbaceous vegetation generally greater than 80% of the total vegetation.
Water	Areas of open water, generally with less than 25% cover of vegetation or soil, including rivers and reservoirs.
Impervious land	Developed areas covered by constructed materials or areas with a mixture of constructed materials and vegetation. Impervious surfaces account for more than 20% percent of total cover.
Unused land	Areas of bedrock, gravel, sand, and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.

The confusion matrix method [42] was used to assess the accuracies of land use maps and four measures, namely, the producer's accuracy (PA, accounting for errors of omission), user's accuracy (UA, accounting for errors of commission), overall accuracy (OA), and overall kappa were computed to evaluate classification accuracy. In addition, this paper employed a transfer matrix to analyze land use change in different stages of urbanization.

2.3.2. Calculating Surface Runoff

The SCS-CN model was employed to calculate the surface runoff for the 77 catchments. The SCS-CN model is a general empirical hydrological model. Compared with the traditional hydrological models, it requires fewer calculation parameters and fewer observation data [43,44]. In recent years, it has been widely used for runoff estimation at different spatial scales [45,46] and several studies have shown that the SCS-CN model can also be applied to estimate the surface runoff in highly urbanized areas where actual hydrological data are difficult to obtain [47,48].

The SCS-CN model is based on the water balance equation, as shown in Equation (1), and two fundamental hypotheses described by Equations (2) and (3) [49–51].

$$P = I_{\alpha} + F + Q, \quad (1)$$

$$\frac{Q}{P - I_{\alpha}} = \frac{F}{S}, \quad (2)$$

$$I_{\alpha} = \lambda \cdot S, \quad (3)$$

where Q is the surface runoff depth (mm), P is the rainfall depth (mm), I_a is the initial abstraction of the rainfall (mm), F is the cumulative infiltration excluding I_a , S represents potential maximum retention or infiltration, and the initial abstraction coefficient λ is a constant that usually ranges between 0.0 and 0.2, and a value of 0.2 was used in this study according to Natural Resources Conservation Service (NRCS) [52].

The surface runoff depth (Q) could be derived from Equations (1) and (2):

$$Q = \frac{(P - I_{\alpha})^2}{P - I_{\alpha} + S}. \quad (4)$$

Equation (4) is valid only when the rainfall value is greater than the value of initial abstraction (I_a). When the rainfall is less than the initial abstraction, the flow value is zero. So, Q could be quantified in the following equation:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}. \quad (5)$$

In Equation (5), S was derived by the dimensionless parameter CN , and the variation range of CN is $0 \leq CN \leq 100$.

$$S = \frac{25400}{CN} - 254, \quad (6)$$

For the SCS-CN model, the parameter CN is the decisive parameter for the size of the runoff, which is primarily related to land use and soil type. The United States Department of Agriculture (USDA) also provides a curve number (CN) look-up table with assignments of different types of land use to facilitate hydrological simulation [52]. Meanwhile, the USDA has created several different hydrologic soil groups (A, B, C, and D) to represent different infiltration capacities of soils [53]. In this paper, we chose B-group soil type and set the antecedent soil moisture condition (AMC) to moderate condition (AMCII). The CN values of different land use types were assigned as: impervious land (98), unused land (86), farmland (78), grassland (61), woodland (58), and water (100). Combining the CN values of different land use types, we used the area weight method to calculate the comprehensive CN values of different catchments to simulate the surface runoff [54].

2.3.3. Analyzing Surface Runoff Changes

The impact of land use change on surface runoff was assessed by evaluating the runoff discrepancies under different land use conditions. The rainstorm on 21 July 2012 (7.21 rainstorm), with a cumulative rainfall of 215 mm, and the rainstorm on 5 July 2017 (7.5 rainstorm), with a cumulative rainfall of 50.9 mm, were chosen for the simulation as the precipitation input (Figure 2). The 7.21 rainstorm, which caused serious losses [55], is considered to be a rainfall event with a 100a return period and the 7.5 rainstorm is considered to be a rainfall event with a 1a return period. These two rainfall events represent extreme precipitation and average precipitation conditions, respectively. The surface runoff of each catchment was simulated by inputting the land use maps of 1984, 1999, 2009, and 2019 individually to drive the SCS-CN model under different rainfall events. Two variables were defined to evaluate the surface runoff changes: the surface runoff depth (Q) and the surface runoff coefficient (α).

The impact assessment was conducted by comparing the difference of runoff variables between the initial land use condition and final land use condition. The equations are given as:

$$\Delta Q = Q_b - Q_a, \quad (7)$$

$$\Delta \alpha = \frac{\Delta Q}{P}, \quad (8)$$

$$\Delta C = \frac{(Q_b - Q_a)}{Q_a} \times 100\%, \quad (9)$$

where Q_a and Q_b are the surface runoff depth (mm) in the initial and final land use scenarios of each stage, P is the rainfall depth (mm), ΔQ and $\Delta \alpha$ represent the absolute amount of runoff change, ΔC represents the relative degree of change. If ΔQ and $\Delta \alpha$ are positive, it indicates that the land use change at this stage leads to an increase in runoff.

2.3.4. Analyzing the Correlation between Surface Runoff Change and Land Use Change

Correlation analysis was used to examine the relationships between surface runoff change and the land use driving factors. Considering that the data did not satisfy the two conditions of linear correlation in the strict sense that (1) the data is obtained from the normal distribution in pairs and (2) the data must be equally spaced data at least in the logical category, this paper used the spearman correlation analysis. It can be inferred that the larger a correlation coefficient is, the more important that factor is in the change of surface runoff.

3. Results

3.1. Land Use/Land Cover Change

We used the independent reference pixels for accuracy assessment. The result is shown in Table 2. The overall accuracy (OA) of the four land use maps in 1984, 1999, 2009, and 2019 were 90.7%, 92.7%, 93.3%, and 94.7%, respectively. OA measures for all four land use maps were better than 90%, and both the PA and UA measures for all four land use maps were greater than 92%.

Table 2. Summary of producer's accuracy (PA), user's accuracy (UA), overall accuracy (OA), and kappa for land use classification of 1984, 1999, 2009, and 2019.

Year	Accuracy	Farmland	Woodland	Grassland	Water	Impervious land	Unused land
1984	PA	87.0%	95.8%	87.5%	95.7%	92.1%	83.3%
	UA	83.3%	92.0%	91.3%	95.7%	92.1%	88.2%
	OA	90.7%					
	Kappa	0.887					
1999	PA	75.0%	100.0%	87.5%	96.2%	92.1%	93.8%
	UA	85.7%	93.8%	93.3%	96.2%	92.1%	88.2%
	OA	92.7%					
	Kappa	0.909					
2009	PA	-	96.8%	90.3%	96.2%	93.3%	88.2%
	UA	-	88.2%	93.3%	100.0%	93.3%	93.8%
	OA	93.3%					
	Kappa	0.915					
2019	PA	-	97.1%	93.8%	96.2%	92.7%	94.1%
	UA	-	91.7%	93.8%	100.0%	95.0%	94.1%
	OA	94.7%					
	Kappa	0.932					

The generated land use maps of the study area are shown in Figure 3. The distribution of land use in the city's core area experienced an obvious change during the study period. Figure 4 shows the land use types and the corresponding percentages in the watersheds. The impervious surface was the main land use type in the study area and it exceeded 50% during the entire study period. The impervious surface was distributed mainly in the area within the third ring road. Concerning the changes in land use, the conversion of land use types mainly occurred in the reduction of farmland and the increase of impervious surface. From 1984 to 2019, impervious land increased the most, which was from 51.49% to 62.75%, while farmland decreased from 14.74% to zero. It should be noted that land use conversion differed in stages. In the first stage (1984–1999), the area of farmland and woodland decreased by more 10%, while the area of impervious land increased rapidly from 51.49% to 66.01%. In the second stage (1999–2009), the proportion of impervious land rose to 75.71% in 2009 and the area of farmland continued to decrease until it almost disappeared in 2009. In the third stage (2009–2019), the proportion of impervious surface decreased by 12.96% and continued to be converted to other land types. Spatially, the area that changed was mainly located between the third ring and the fifth ring, and the amount of change in the south was relatively larger than that in the north.

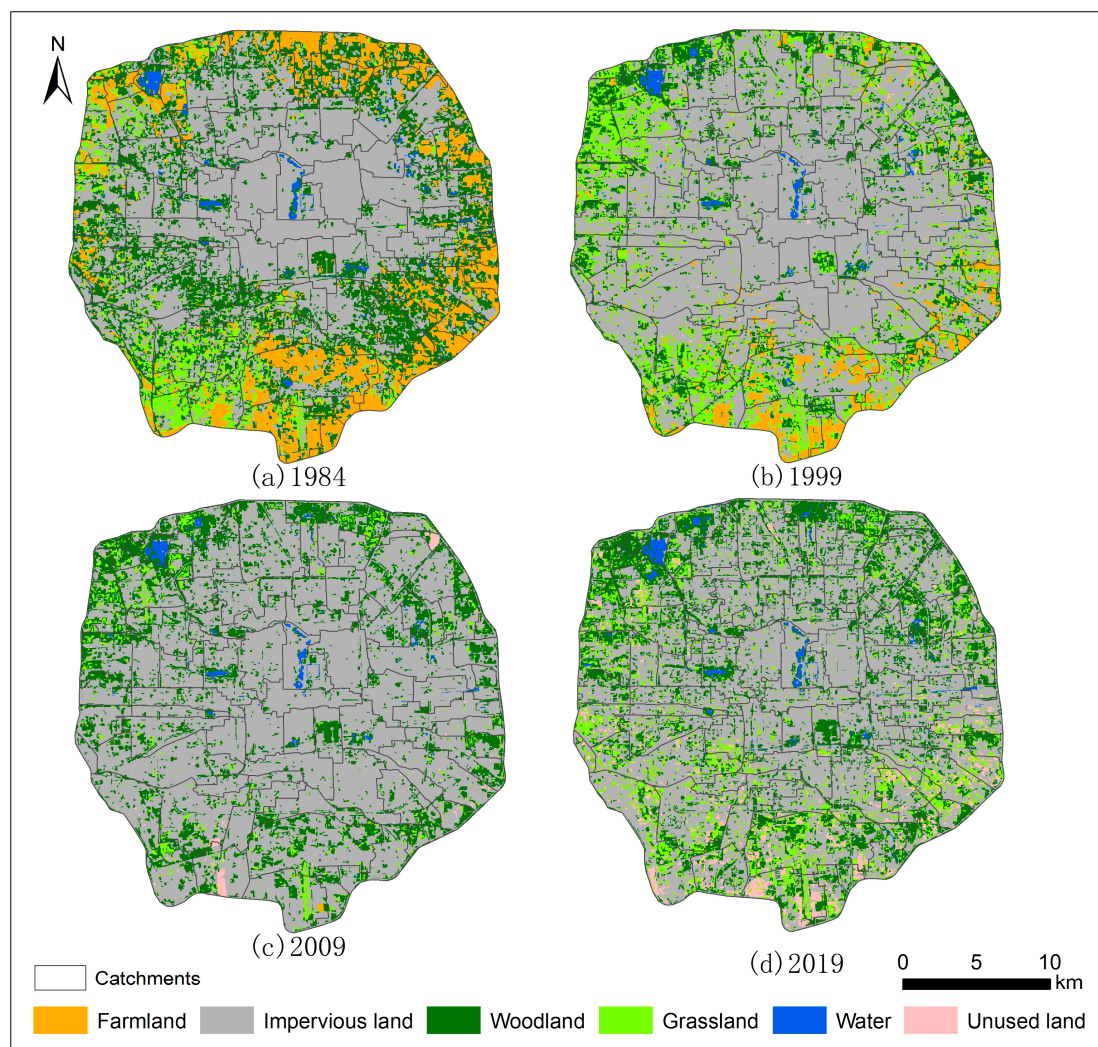


Figure 3. Land use maps of the study area in (a) 1984, (b) 1999, (c) 2009, and (d) 2019.

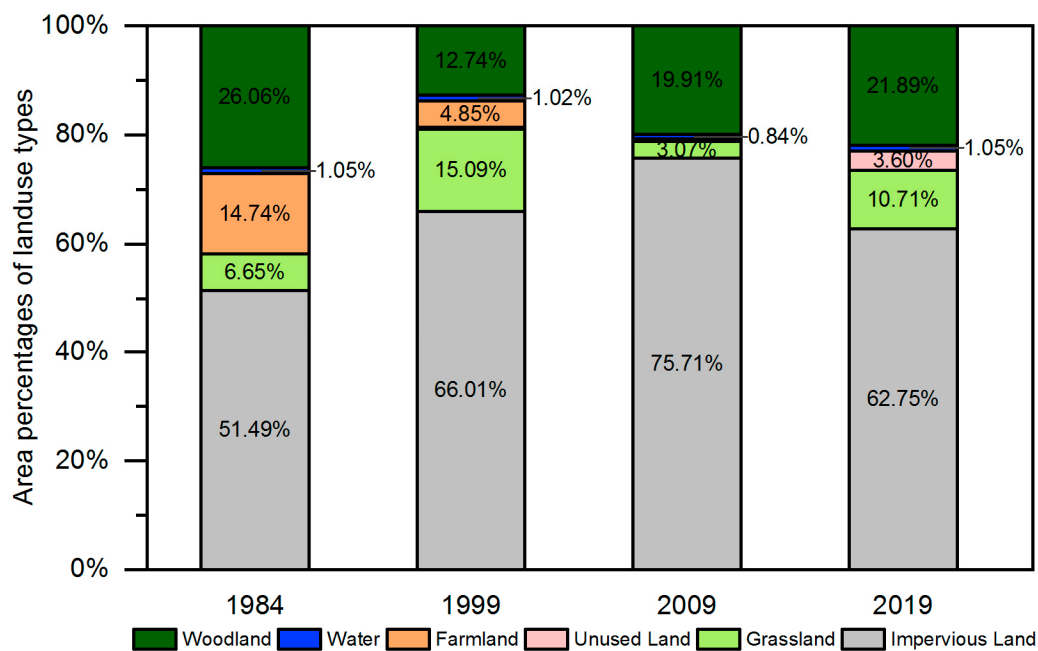


Figure 4. Percentage of land use types of the study area in 1984, 1999, 2009, and 2019.

3.2. Surface Runoff Characteristics

The average surface runoff under different land use conditions and the rainfall return period of 1a and 100a are shown in Figure 5. Under the four different land use conditions, the average surface runoff depth varied from 160.64 to 181.00 mm and the surface runoff coefficient varied from 0.75 to 0.84. Both the average runoff depth and the runoff coefficient at the rainfall return period of 100a were much larger than the values calculated at the rainfall return period of 1a.

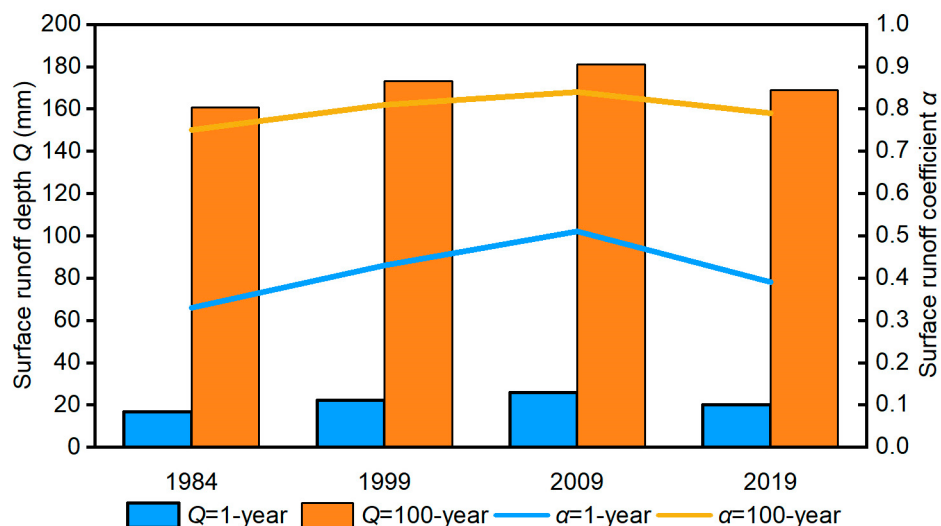


Figure 5. Average runoff depth Q (mm) and runoff coefficient α with the rainfall return period of 1a and 100a, under the land use conditions of 1984, 1999, 2009 and 2019.

The spatial distribution characteristics of the surface runoff with the rainfall return periods of 1a and 100a based on the land use in 2019 are shown in Figure 6. The surface runoff was basically symmetrical from east to west and the runoff in the north was slightly larger than that in the south. The runoff gradually decreased from the central urban area to the outside rings. Comparing the runoff result with the rainfall return period of 100a to that with the rainfall return period of 1a, the amount of

surface runoff was larger and the distribution was more uniform under extreme precipitation condition with the return period of 100a. This means that extreme precipitation would greatly increase the urban flood risk.

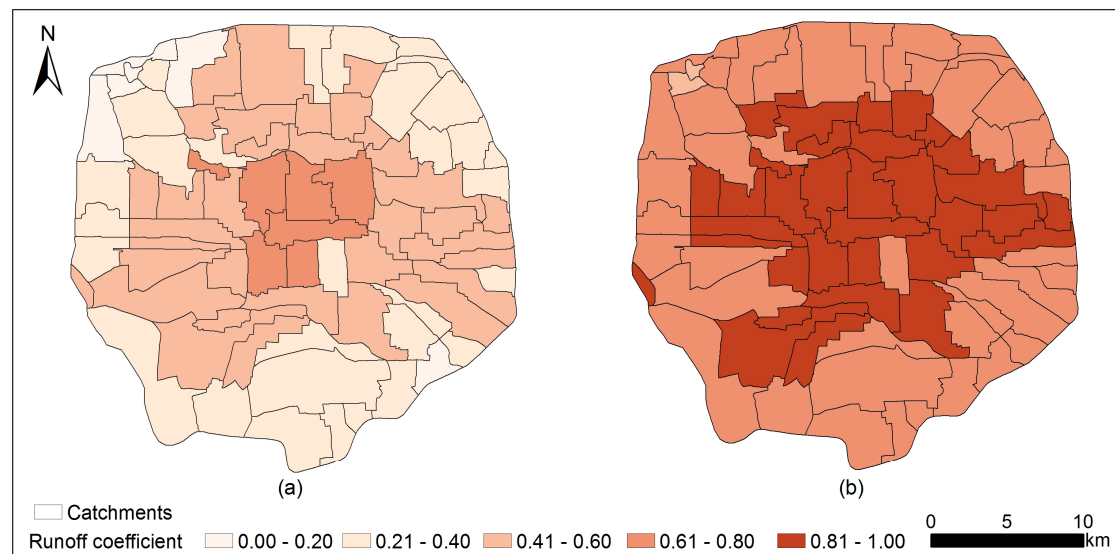


Figure 6. Spatial distribution characteristics of surface runoff with the rainfall return periods of (a) 1a and (b) 100a under land use condition of 2019.

3.3. The Impact of Land Use Change on Surface Runoff

Urbanization leads to increased impervious surfaces, resulting in surface runoff increases. Table 3 shows the increments of surface runoff at different stages under the rainfall return periods of 1a and 100a. Taking the rainfall condition for the return period of 100a as an example, the average surface runoff depth increment ΔQ at the three stages was 12.66, 7.7, and -12.18 mm, respectively. The surface runoff coefficient increment $\Delta\alpha$ at the three stages was 0.06, 0.03 and -0.05 , respectively.

Table 3. Changes in surface runoff parameters at different stages under the rainfall return periods of 1a and 100a.

Return Period	Stage	ΔQ (mm)	$\Delta\alpha$	ΔC (%)
100a	1984–1999	12.66	0.06	7.88
	1999–2009	7.70	0.03	4.44
	2009–2019	-12.18	-0.05	-6.73
1a	1984–1999	5.36	0.11	31.96
	1999–2009	3.85	0.08	17.40
	2009–2019	-5.87	-0.12	-22.59

Figure 7 shows the spatial distribution of surface runoff variation at different periods under the rainfall return period of 100a. During 1984–1999, 77% of the catchments showed an increasing trend. The catchment area with a large runoff growth rate was mostly located between the third ring and the fifth ring. During 1999–2009, the catchment area with an increased depth of runoff was mainly distributed in the southern part of the fifth ring and the runoff decline area was mainly distributed in the western part of the Fourth Ring Road. During 2009–2019, the runoff coefficient decreased significantly for most catchments, and the changes of the surface runoff in the southern areas were more significant than that in the northern areas.

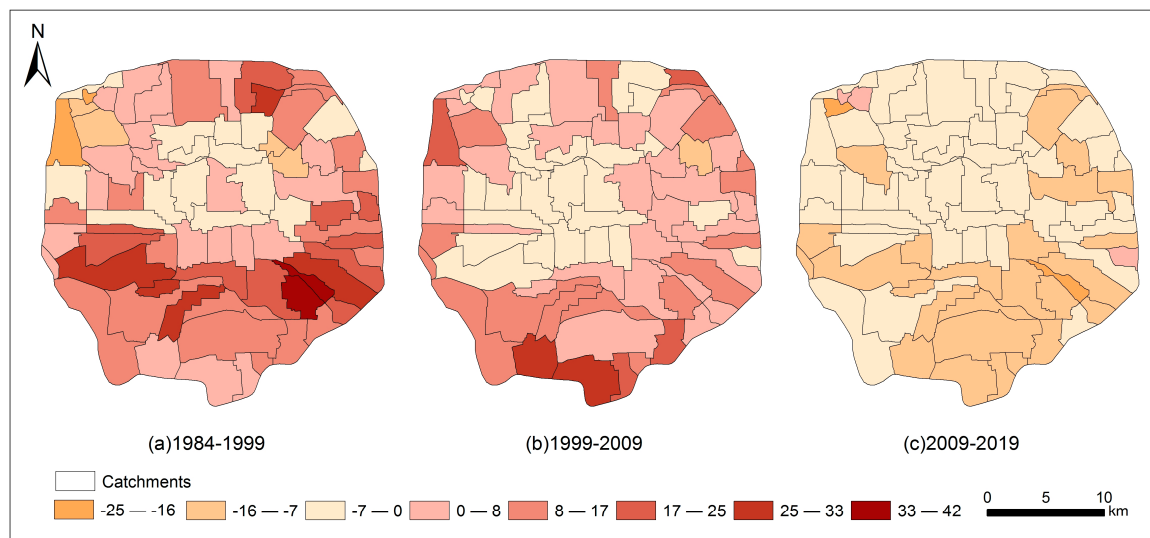


Figure 7. Variation in surface runoff over the periods of (a) 1984–1999, (b) 1999–2009, and (c) 2009–2019 under the rainfall return period of 100a.

3.4. Relationship between Land Use Change and Surface Runoff Change

Spearman correlation analysis was used to examine the relationships between surface runoff change (ΔQ) and land use change. The correlation coefficients between ΔQ and change rate of each land use type for 77 catchments during the different periods under the rainfall return period of 100a are provided in Table 4.

Table 4. Spearman correlation coefficients between surface runoff change and land use change under the rainfall return period of 100a.

Period	Impervious Land (PI)	Woodland (PW ₁)	Grassland (PG)	Farmland (PF)	Unused Land (PU)	Water (PW ₂)
1984–1999	0.924 **	−0.912 **	−0.072	−0.112	0.112	−0.299 **
1999–2009	0.920 **	−0.212	−0.703 **	−0.568 **	0.305 **	−0.204
2009–2019	0.894 **	−0.477 **	−0.474 **	−0.181	0.387 **	−0.180

Note: ** indicate significant at the 0.01 level.

These results show that surface runoff change was positively correlated to the change in impervious land and negatively correlated to the change in woodland, grassland, farmland, and water. The results are consistent with common sense that the increase in impervious land probably causes the increase in surface runoff, but the greater amount of woodland, grassland, farmland, and water probably lead to a decrease in surface runoff. During 1984–1999, the degree of correlation between ΔQ and land use factors decreased in the order of PI (0.924), PW₁ (−0.912), and PW₂ (−0.299), which were significant at the 1% level. During 1999–2009, the most relevant factor with ΔQ was PI (0.920), followed by PG (−0.703), PF (−0.568), and PU (0.305). During 2009–2019, the significant correlations were found between ΔQ and PI (0.894), PW₁ (−0.477), PG (−0.474), and PU (0.387). The impervious land change is recognized as the predominant driving factor for the surface runoff change during the whole period.

4. Discussion

In this paper, the SCS-CN model was used to calculate surface runoff. In order to improve the applicability of the model in the study area, the experimental result of Fu et al. [38] on soil types in Beijing were used to set the soil type of the model and the moderate antecedent moisture condition (AMCII) was selected to reflect the average runoff situation in Beijing. The CN values of different land use types were determined according to the CN value list issued by NRCS [52]. The results showed

that the SCS-CN model was effective and reasonable. From 1984 to 2019, the surface runoff of Beijing's central urban area showed a trend of "rapid increase-slight increase-decrease", which was consistent with the "rapid development-slow development-adjustment" development of Beijing city [56].

The increase of surface runoff in the early stage was mainly caused by the transformation of farmland and woodland to impervious land, while the decrease in surface runoff in the later stage was related to the construction of "sponge city" in Beijing [57]. The term sponge city is similar to the term "low impact development (LID)", which means that the city, like a sponge, has good flexibility in adapting to environmental changes and responding to natural disasters brought by rainwater. Sponge city construction measures include rain gardens, ecological detention facilities, green roofs, and so on [58,59]. In recent years, Beijing has actively promoted the construction of sponge city and has effectively reduced surface runoff [60].

The existing research on the hydrological effect of urbanization has mainly focused on the community [61,62] or catchment scale [63,64]. This work provided the spatial-temporal variation in runoff at the urban scale. The display of land use development and assessment of surface runoff can help researchers and policymakers to better understand urban development and environmental response [65]. The results also can be used for urban renewal strategy-making for urban rainstorm waterlogging prevention and control. The catchment area with a high value of surface runoff has a high potential of waterlogging risk under the heavy rainfall condition. Therefore, more attention should be paid to these areas during future land use planning. It is necessary to increase rainwater gardens, water-sinking green spaces, green roofs, and other facilities in the high waterlogging risk areas.

The interactions between social and ecological system are complex and non-linear [66]. Besides land use change, human activities that also exert great influences on runoff include the following: irrigation [67,68], construction and operation of dams and reservoirs [69,70], water conservancy projects [71], utilization of groundwater [72], and urban drainage pipe systems [73]. This paper focused on evaluating the impact of land use change on surface runoff and the other human and environmental factors that may affect surface runoff require further exploration in the future.

5. Conclusions

China has experienced a trend of rapid urbanization in the last 40 years. Reducing the urban disaster risk brought about by the urbanization process has been a long-term goal of urban planning and city management. Quantitative research on the runoff changes brought about by the urbanization process is of great significance to urban planning and flood control. This paper used GIS and remote sensing technology, combined with the SCS-CN model, to simulate the changes of runoff and assessed the impact of land use change on surface runoff in the core urban area of Beijing. The conclusions are summarized as follows:

- (1) Impervious land was the major land use type in Beijing's central area. The percentage of impervious land increased by 24.22% from 1984 to 2009 but decreased by 12.96% from 2009 to 2019;
- (2) Both of the surface runoffs calculated with the return period of 100a and 1a showed the trend of first increasing then decreasing and the trend was consistent with the variation in impervious land during the three stages of the study area;
- (3) The changes in surface runoff were positively correlated with the changes in impervious land, but negatively correlated with the changes in woodland, grassland, farmland, and water. The urbanized impervious land use was the predominant driving factor in the surface runoff change during the period of 1984–2019 in Beijing's central area.

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