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The effect of land use/cover change on surface runoff in Shenzhen region, China

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Abstract

Shenzhen is one of the special economic zones in China. It has been growing rapidly from rural land to an industrial city since the mid-1980s. With the process of urbanization, flooding has become a threat to the security of the city area. In this study, Buji River basin in Shenzhen Region was selected to investigate the effect of urbanization on surface runoff and peak discharge. Land use data were obtained from LANDSAT images in 1980, 1988, 1994, and 2000, and surface runoff in the same period was simulated by SCS model. Results showed that urbanization played an important factor intensifying the flood process. Increase of urbanized land and decrease of farmland might be the main reasons for increasing runoff. At 10%, 50% and 90% rainfall probability (the rainfall probability of 10% means 10-year return period of moist year, 2-year return period of normal year and 10-year return period of dry year), the increase of runoff coefficient was 12.6%, 20.7% and 33.5% respectively under relatively dry soil moisture condition, however, and the value was 2.5%, 4.3% and 6.9% respectively under relatively wet soil moisture condition. Urbanization led to obvious increase in the maximum flood discharge and decrease in runoff confluence time. At 1%, 2% and 5% rainfall probability, the increase of the maximum flood discharge was 20.2%, 23.0% and 28.9% respectively, under relatively dry soil moisture condition. The corresponding value was 1.3%, 1.6% and 2.6% respectively under relatively wet soil moisture condition. Due to urbanization in the past 20 years, runoff coefficient increased 13.4% and the maximum flood discharge increased 12.9% on average.

Keywords: Urbanization; Surface runoff; Shenzhen; Land use/cover

1. Introduction

Change in runoff characteristics induced by urbanization is important for understanding the effects of land use and cover change on earth surface hydrological processes. With urban land development, impermeable land surfaces enlarge rapidly, the capability of rainfall detention declines sharply and runoff coefficient increases. Urbanized land usually leads to a decrease in surface roughness; hard road and drainage system can greatly shorten the time of runoff confluence. Therefore, urbanized area would become more susceptible to flood hazard under conditions of high precipitation intensity (Cheng and Feng, 1994).

Since the mid-1980s, Shenzhen has been growing rapidly from rural land to an important industrial city, and becoming one of the special economic zones in China. Intensive human activities and land-use change have dramatically affected the regional water environment. Water shortage, flood hazards, and water pollution became more serious in the process of urbanization (Hall, 1984). According to statistical data, there were 4 flood events from 1980 to 1987, 6 floods from 1988 to 1993, and 8 floods from 1994 to 2000. From 1981 to 1990, 13 persons died in 6 flood events, and direct economic loss was 283.7 million RMB Yuan; from 1991 to 2000, 54

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persons died in 12 flood disasters, and direct economic loss was 2603.78 million RMB Yuan (Yuan et al., 2003). Thus, for understanding the mechanism and prevention of flood disaster, it is necessary to explore the effect of urbanization on surface runoff in this specific region.

2. Materials and methods

2.1. The study area

Shenzhen region, at the central coastal area in southern Guangdong Province, is the passageway from mainland China to Hong Kong (Fig. 1). It has a total land area of 1948.69 km^2. According to soil horizontal zonality, the main soil types are yellow soil, red soil and lateritic red soil. Moreover, Shenzhen was once a rural area, so types of soil being used also include latosol, paddy soil, seashore sand soil and saline soil. Vegetation covers 50–80% of the land area. With tropical oceanic monsoon climate, the average annual precipitation from 1952 to 1992 was 1882.8 mm, and rainfall in the flood season from April to September made up 84.5% of the annual total.

In Shenzhen region, there are 160 rivers, among which 13 rivers with drainage basin areas larger than 10 km^2 and 5 river basins larger than 100 km^2. We selected Buji River Basin as the study area. The upper reach of Buji River flows through Buji Town and its lower reach flows across the downtown of Shenzhen City. The length of Buji River is 17.72 km and the total area of its drainage basin is 56.88 km^2. In recent years, with economic development, the urbanization level in Buji River Basin has been rising rapidly.

2.2. Data sources

Land use/cover data were acquired from LANDSAT images in 1980 (MSS), 1988 (TM), 1994 (TM) and 2000 (TM). Using topographic contour data (1:10,000) of the study area, a vector DEM was generated. For the purpose of overlaying with some pixel data, such as land use and soil type, etc., a DEM map at a resolution of 30 × 30 m was also obtained. Meteorological data including annual and monthly precipitation (1953–2000), average precipitation and runoff, annual maximum rainfall in 24 h (1954–1993) and precipitation data of some typical rainstorms were obtained from local meteorological station.

2.3. SCS model

It is difficult to use the traditional hydrological methods to simulate the rainfall–runoff process because the hydrological and meteorological data are generally insufficient. Moreover, it is not possible to input remote sensing data directly to most traditional hydrologic models because of the incompatibilities

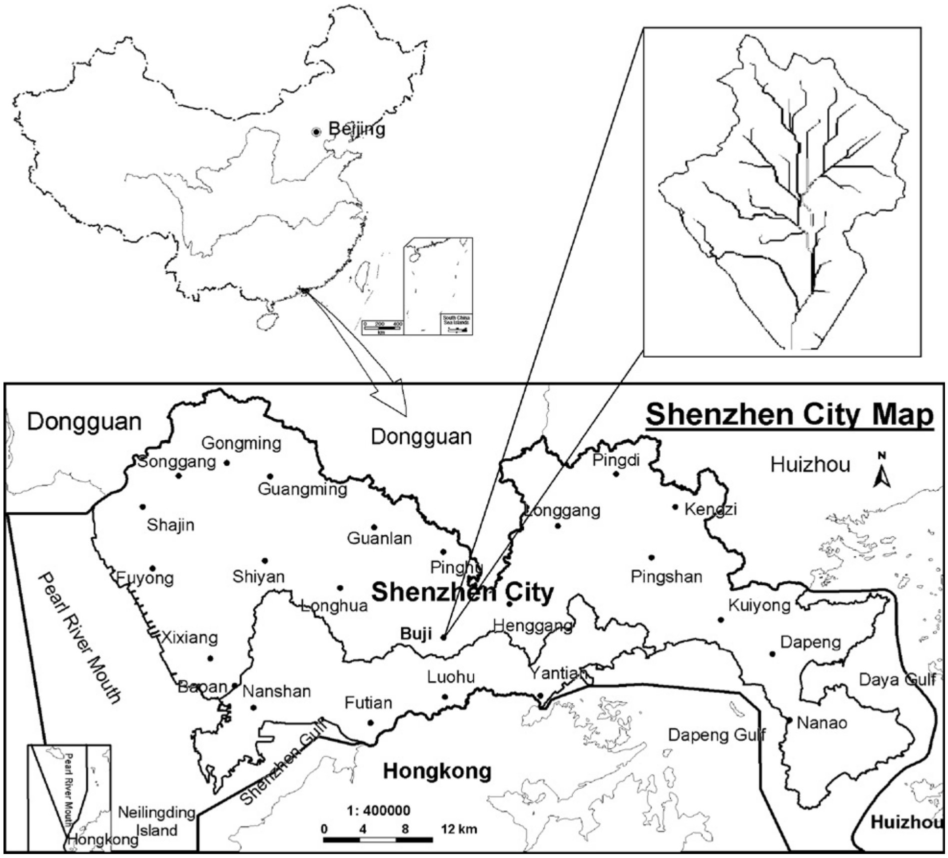

Fig. 1. Location map of Shenzhen region.

between model structure and characteristics of remote sensing data (Rango, 1985). And what's more, the land use data from remote sensing data does not suit the parameters and structure of the traditional hydrological models (Lu, 1990; Wang, 1999). Therefore the remote-sensing-based hydrological model may be considered as useful in this analysis.

SCS model (U.S. Soil Conservation Service, 1972) has been widely used internationally for water resources management and planning (Hawkins, 1978; Ragan and Jackson, 1980; Slack and Welch, 1980; Hawkins, 1993; Lewis et al., 2000). It has also been introduced and applied by some scholars in China (Zhang, 1987; Mu, 1991; Wei and Xie, 1992; Pan, 1996; Li, 1997). Because major input parameters for the SCS model are land use and soil type, the SCS model is potentially compatible with remote sensing input. The SCS model can be expressed as:

$$\left.\begin{array}{ll} Q = \dfrac{(P-0.2S)^2}{P+0.8S}, & P0.2S \\ Q = 0 & , P < 0.2S \end{array}\right\} \quad (1)$$

where Q is direct runoff, P is storm rainfall, and S is potential maximum retention or infiltration. For convenience and standardization application of Eq. (1), S is expressed in the form of a dimensionless runoff curve number (CN):

$$S = \frac{25400}{\mathrm{CN}} - 254 \quad (2)$$

In which, CN represents the runoff potential of the land cover-soil complex governed by soil property, cover type, and hydrologic condition of the land surface. CN also depends on the antecedent wetness of the drainage basin. Three antecedent moisture conditions (AMC) were defined as dry, moderate, and wet, denoted as AMCI, AMCII, and AMCIII, respectively.

3. Results and discussion

3.1. Determination of model parameters

According to the SCS model, CN value is related with land use type, soil type, and AMC. The land use types of Buji River Basin were obtained (Table 1). The urbanization level, the proportion of urbanized area to the total land area, was 2.02%, 38.94%, 48.78%, and 58.72% in 1980, 1988, 1994, and 2000, respectively.

The soil data were compiled from "Landform of Shenzhen City", according to soil classification categories in SCS model (GIGS, 1983). Based on CN values in the SCS model, local soil infiltration properties and other published results, CN values in the Buji River Basin were estimated (Rango, 1985; Zhang, 1987; Maidment, 1992; Pan, 1996). Estimated CN values for land surfaces with different infiltration properties under AMCII condition are shown in Table 2.

Topography is one of the main factors affecting runoff confluence process in a river basin. The drainage system is the foundation to simulate the grid flux. Using ArcGrid module of ARC/INFO software, the drainage system of Buji River Basin was obtained by processing the depressed area of DEM and defining the stream directions based on pixel data of DEM.

3.2. Model verification

Based on precipitation data from 1956 to 1995 and the mean annual rainfall and runoff, the SCS model was verified by comparing the estimated runoff with in situ measured data. The absolute errors in the estimated runoff ranged from 40 to 90 mm and the relative errors were 5–9%.

Table 2
Estimated CN values (AMCII)

Land use type	Land surface infiltration categories			
	A	B	C	D
High density urban land	90	93	94	95
Low density urban land	60	74	83	87
Paddy field	67	78	85	89
Forest	25	55	70	77
Shrub and grassland	36	60	74	80
Orchard	40	62	76	82
Wetland	32	58	72	79
Barren Land	72	82	88	90
Water	98	98	98	98

Land surface infiltration categories: A, high infiltration rate; B, moderate infiltration rate; C, low infiltration rate; D, no infiltration.

Table 1
Land use types in Buji River Basin in 1980, 1988, 1994 and 2000

Year	Index	Urban land with high density	Urban land with middle and low density	Farmland	Orchard	Forest	Grassland	Water	Wetland	Unused land
1980	A^{a} (km^2)	0.00	2.02	18.50	0.00	24.80	7.64	1.15	0.31	2.77
	P^{a} (%)	0.00	3.53	32.35	0.00	43.37	13.36	2.01	0.54	4.84
1988	A (km^2)	1.28	20.99	4.45	8.77	17.89	0.74	0.56	0.01	2.48
	P (%)	2.23	36.71	7.79	15.33	31.29	1.30	0.99	0.02	4.34
1994	A (km^2)	2.85	25.04	2.27	6.59	13.73	0.00	0.70	0.02	5.98
	P (%)	4.98	43.80	3.97	11.53	24.01	0.00	1.22	0.04	10.46
2000	A (km^2)	6.08	27.50	1.52	4.45	13.51	0.00	0.87	0.02	3.24
	P (%)	10.63	48.09	2.65	7.77	23.63	0.00	1.52	0.04	5.66

[a] A represents the area of land; P represents the proportion of the area of a specific land to the total area.

Table 3
Runoff coefficients in Buji River Basin

Rainfall probability	Year	Antecedent soil moisture conditions			
		AMCI	AMCII	AMCIII	Mean
90%	1980	0.22	0.46	0.74	0.47
	1988	0.23	0.48	0.76	0.49
	1994	0.27	0.52	0.79	0.52
	2000	0.29	0.53	0.79	0.54
50%	1980	0.37	0.61	0.83	0.60
	1988	0.39	0.63	0.85	0.62
	1994	0.43	0.66	0.86	0.65
	2000	0.44	0.67	0.87	0.66
10%	1980	0.54	0.74	0.90	0.73
	1988	0.56	0.76	0.91	0.74
	1994	0.60	0.78	0.92	0.77
	2000	0.61	0.79	0.92	0.77

AMCI: low soil moisture; AMCII: moderate soil moisture; AMCIII: high soil moisture.

Simulated result was soundly consistent with the actual situation (Yuan and Shi, 2001). Furthermore, simulated maximum flood peak discharges at 1%, 2%, and 5% storm probability (see later explanation) were compared with the data in “Plan of Urban Flood Control in Shenzhen” (1994). The relative error was lower than 10%, showing a reliable simulated result. Thus, the SCS model could be applied in the regions where the hydrological data are limited.

3.3. Runoff generation

The runoff coefficient is an index reflecting hydrological characteristics on different land surfaces. In this study, a runoff coefficient in each pixel was calculated with the SCS model. Runoff coefficient contour maps under different 24-h maximum precipitation intensities with probabilities of 90%, 50% and 10% were obtained, respectively (Table 3). The rainfall probability of 1%, 2%, 5%, 10%, 50% and 90% means the frequency of 1% (100-year return period of moist year), 2% (50-year return period of moist year), 5% (20-year return period of moist year), 10% (10-year return period of moist year), 50% (2-year return period of normal year) and 90% (10-year return period of dry year).

Generally, the runoff coefficient increased when antecedent soil moisture content became higher. On average, runoff under wet soil conditions was two times higher than the dry soil condition. From 1980 to 2000, under antecedent dry soil condition, the runoff coefficient increased by 31.82%, 16.22% and 12.96% for the 90%, 50% and 10% storm probabilities, respectively; under antecedent wet soil condition, it increased by 6.76%, 4.82% and 2.22%, respectively. Under the same precipitation condition, the net increase in runoff by urbanization was in the order of CAMCI > CAMCII > CAMCIII, demonstrating that if antecedent soil moisture increases, the land use change will have a smaller effect on runoff. Many natural and social factors, such as land use, soil texture, antecedent soil moisture, and rainfall intensity could influence runoff, and their interactions are complicated. Urbanization could lead to higher runoff coefficient and thus intensify flood disasters.

3.4. Flood discharge

Using the SCS model, we simulated the flood peak discharge, and 24-h flood discharge for 36 scenarios, under different rainfall probabilities, and different antecedent soil moisture conditions, in 1980, 1988, 1994, and 2000 (Table 4).

Under all rainfall probability levels, the flood peak discharge increased with increasing soil moisture. In the case of 1%, 2% and 5% rainfall probabilities, the flood peak discharge under AMCIII was 32.93%, 39.64%, and 58.37% higher than that under AMCI, respectively, for all the 4 years. Simultaneously, the 24-h flood discharge under AMCIII was 51.72%, 59.59%, and 76.20% higher than that under AMCI, respectively.

Under all soil moisture conditions and at all the rainfall probability levels, the flood peak discharge in 2000 was obviously larger than that in 1980. In the case of AMCI, the maximum flood peak discharge of three designed rainfall floods at probabilities of 1%, 2% and 5% increase by 20.2%, 23.0% and 28.9% respectively; in the case of AMCIII, the flood peak discharge of the three designed

Table 4
The flood peak discharge and 24-h flood discharge under different rainfall probabilities

Rainfall probability	Year	Flood peak discharge ($m^3 s^{-1}$)				24-h flood discharge ($\times 10^4$ m^3)			
		AMCI	AMCII	AMCIII	Mean	AMCI	AMCII	AMCIII	Mean
1%	1980	438.7	611.5	671.5	573.9	1058.8	1491.7	1756.3	1435.6
	1988	515.2	645.5	690.2	617.0	1167.6	1561.3	1802.0	1510.3
	1994	551.7	671.4	688.1	637.1	1254.5	1606.6	1821.8	1561.0
	2000	549.7	670.1	682.2	634.0	1270.2	1618.1	1828.4	1572.2
2%	1980	366.5	533.5	605.7	501.9	887.5	1302.9	1562.9	1251.1
	1988	440.2	567.1	619.9	542.4	986.7	1370.1	1607.7	1321.5
	1994	478.0	599.0	619.9	565.6	1069.5	1415.3	1626.5	1370.4
	2000	476.2	600.4	613.4	563.3	1085.5	1425.1	1633.0	1381.2
5%	1980	260.3	421.4	509.2	397.0	648.0	1041.3	1296.4	995.2
	1988	319.7	456.0	521.8	432.5	739.0	1103.1	1335.3	1059.1
	1994	367.7	489.6	527.0	461.4	816.1	1147.0	1354.6	1105.9
	2000	366.0	494.9	522.5	461.1	830.3	1155.6	1358.9	1114.9

rainfall floods increased by 1.6%, 1.3% and 2.6%, respectively. And the 24-h flood discharge showed a similar trend from 1980 to 2000. This change is assumed to result from rapid urbanization during this period. The flood peaks in 2000 took place generally 1–2 h earlier than those in 1980. This might indicate that urbanization led to quicker runoff confluence and higher flood discharge.

4. Conclusions

In the past two decades, the Shenzhen region experienced a rapid urbanization process characterized by sharp decrease in farmland and increases in urban land. Human activities and land-use change have dramatically affected the regional water environment. Water shortage, flood hazards, and water pollution have become more serious in the process of urbanization. Many natural and social factors, such as land use, soil texture, antecedent soil moisture, and rainfall intensity may influence runoff, and their interactions are complicated. The SCS-model simulation on the hydrological parameters in the Buji River Basin revealed that urbanization could lead to higher runoff, greater flood peak discharge and shorter runoff confluence times, and thus greater risk of flood disasters.

Storm intensity and soil antecedent moisture condition have important effects on runoff generation and flood process. When the soil antecedent moisture condition is dry, the increment of runoff coefficient of the rainfall probabilities of 10%, 50% and 90% was 12.96%, 16.22% and 31.82% respectively from 1980 to 2000. When the soil antecedent moisture condition is wet, the index was 2.22%, 4.82% and 6.76% respectively. When the soil antecedent moisture condition is dry, the increment of maximum flood peak discharge of the rainfall probabilities of 1%, 2% and 5% was 20.2%, 23.0% and 28.9% respectively from 1980 to 2000. When the soil antecedent moisture condition is wet, the index was 1.6%, 1.3% and 2.6% respectively, which decreases rapidly as the soil antecedent moisture changes from dry to wet.

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