Evaluating urbanization and its impacts on local hydrological environment change in Shijiazhuang, China, using remote sensing

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Abstract This study illustrates urbanization in Shijiazhuang city and its impacts on change in local micro-climatic and hydrological environments using remote sensing. First, a pair of Landsat TM images of the study area acquired in 1987 and 2001, were used to detect urban expansion and associated land cover change. Together with detecting urban expansion and associated land cover/use change, we used the remote sensing data in the thermal-infrared band to analyse the thermal environmental change due to urbanization. In order to evaluate the impacts on hydrological cycle, we calculated and compared the water balance in 1985–1989 and 1999–2003. Results suggest the change in water balance due to urbanization is significant. Evapotranspiration is reduced by about 20%, equivalent to 100 mm per year, and the annual surface runoff generation increases 32%. However, a significant enlargement of the urban heat island is also observed.

Key words hydrological change; Shijiazhuang; urbanization

INTRODUCTION

Urbanization is an important aspect of human activity in influencing the environment. During the process of urbanization, reflectivity of land surface is considerably changed when large areas of natural or agricultural lands are converted to built-up areas. These changes strongly affect the atmosphere/land surface energy exchange (Quattrochi & Ridd, 1994; Grimmond & Oke, 1995), as well as local weather and climate regimes (Oke, 1987; Roth *et al*., 1989; Changnon, 1992). As for hydrological cycle, most of the processes between land and atmosphere, surface and subsurface (Hammer, 1972; Grimmond & Oke, 1991) are influenced by urbanization.

During the last two decades, China has experienced rapid economic development. Accompanying the significant growth in economy, landscapes of China have been largely changed due to urbanization. In the North China Plain, where water shortage is the most important environmental problem, the changes associated with urbanization have caused the deterioration of the vulnerable hydrological environment (Shen *et al*., 2005). Therefore, it is necessary for urban planning and hydrological modelling to study how urbanization affects the environment.

In this case study, we attempt to evaluate the influence of urbanization on local hydrological environment by analysing the implications to hydrological environmental change from the perspective of remote sensing.

STUDY AREA AND METHOD

Study area

The study area is located in eastern China, between the range of 114°23′–114°42′E and 37°58′–38°60′N, with an area of about 341.63 km^2, which covers the whole city of Shijiazhuang and its near suburban areas. Shijiazhuang city lies on an alluvial fan of the Hutuo River, with a slight slope of about 1.5‰ declining from northwest to southeast. The semiarid monsoon climate determines its precipitation, which is only about 500 mm/year, around two thirds of which falls between July and September. The Hutuo River runs through the north side of Shijiazhuang, and has become a seasonal river over time, mainly due to the extensive exploitation of water resources.

Shijiazhuang is the largest city in Hebei province due to its important position in administration, culture, economy and transportation. The population was around 2.2 million in 2005. During the last 20 years of economic reform, urban expansion of Shijiazhuang was very significant (Xiao *et al.*, 2006). According to the economic annals, its built-up area was 165.5 km^2 in 2001.

Most of the water resource for this city is presently sourced from groundwater because the nearby river has already dried up and become a seasonal river for nearly three decades. Recently, a small proportion of the water resource was contributed by a reservoir to the west.

Data and processing

The satellite remote sensing data used in this study are two sub-scenes of Landsat Thematic Mapper images recorded on 29 June 1987 and 10 May 2001, respectively. After geometrically correcting to the UTM projection, the two images were separately classified using a supervised classification method (see Xiao *et al.*, 2006) and statistical characteristics were calculated for different land cover/use classes. Change detection was conducted for the built-up area. Finally, impacts of these changes on the hydrological cycle are evaluated with linking to some ground statistical data.

Normalized Difference Temperature Index (*NDTI)*

A consequent environmental phenomenon occurring with urban expansion is the enlargement of urban heat island. Even though heat island is a meteorological term related to the increase of air temperature above the urban area, land surface temperature observed by satellite is usually used to evaluate heat island. In this study, we use the normalized difference temperature index (*NDTI*) to evaluate thermal environmental change with regard to urban expansion.

$$NDTI = \frac{T - T_{\min}}{Ts_{\max} - T_{\min}} \quad (1)$$

where T is surface temperature, and $T_{\min}$ and $T_{\max}$ are the minimum and maximum temperature on satellite image.

Impervious surface cover

Impervious surface cover (*ISA*) is an indicator to describe the fractional cover of urban or built-up area (Ridd, 1995; Carlson & Arthur, 2000). *ISA* constitutes the fractional cover of a pixel for which the surface can neither evaporate water nor permit rainwater to penetrate. A reasonable definition of ISA can be addressed by satellite (Carlson & Arthur, 2000):

$$ISA = (1 - f_v)_{bu} \quad (2)$$

where the subscript, *bu*, indicates that the quantity is defined only for regions classified as built-up; f_v is fractional vegetation cover, calculated by:

$$f_v = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \quad (3)$$

where, $NDVI_{\max}$ and $NDVI_{\min}$ are the vegetation indices for dense vegetation and bare soil, respectively. In this study, we use 0.8 and 0.05 for these two parameters according to our previous field observation (Shen *et al.*, 2006).

Water balance evaluation

In order to evaluate the impacts of urbanization on hydrological cycle, we calculate the water balance before and after fast urbanization. The water balance for a single rainfall event can be expressed as:

$$P = E + R + Int + Inf \quad (4)$$

where P is total precipitation of a rainfall event; Int is interception by vegetation; E is evaporation during rainfall event; Inf is infiltration into soil; and R is runoff. On an annual basis, the water balance equation can be simplified as:

$$P + Irr = R + ET + \Delta S \quad (5)$$

where, Irr is irrigation, which is calculated as the difference between crop water requirement and precipitation; ΔS is change in soil water storage, which is assumed as zero in this study. The optimum crop water consumption in the wheat–maize double cropping system of this area is estimated as around 870 mm per year according to a 10-year field experiment (Sun & Shen, unpublished data); therefore, the annual irrigation for a pure grid of crop field is calculated as the deficit between the optimum crop water consumption and precipitation.

The annual runoff R is calculated by:

$$R = \begin{cases} ISA \cdot P & P \le 320mm \\ ISA \cdot P + (1 - ISA) \cdot R_{eff} & P > 320mm \end{cases} \tag{6}$$

R_{eff} is effective runoff. The following equation can be used to calculate the effective runoff in North China Plain when annual precipitation is more than 320 mm, which is a threshold value for producing effective runoff:

$$R_{eff} = 0.0002 \cdot (P - 320)^2 + 0.1309 \cdot (P - 320) \tag{7}$$

RESULTS

Land cover change detection

Figure 1 illustrates land cover maps of Shijiazhuang City in 1987 and 2001. In these two maps, the study area is classified into nine classes: urban, residential, trees, orchards, vegetable fields, crop land, grassland, water body, and sandy/soil (Xiao *et al.*, 2006). Urban and residential areas are treated as built-up areas in the analysis of urbanization. Trees and orchards are combined as forest. Vegetable fields and crop land are combined as farmlands. Water, grassland, and sandy/bare soil are combined as other.

An obvious change according to these two class maps is the evident enlargement of built-up area and the decrease in trees (including orchards) and cropland. Table 1 shows the statistics of changes between these two years. The built-up area has increased 27.4% during the last 14 years from 13 895 ha to 17 698 ha. In contrast, forest (trees and orchards) has been reduced by about 56% from 3376 to 1488 ha. A net reduction of around 2350 ha agricultural land disappeared due to urbanization. Figure 2 shows that around 3800 ha of expended built-up area during these 14 years are distributed around the old territory of the city.

The influence of urbanization on thermal environment

An evident effect of urbanization is that the thermal environment will be significantly changed because urbanized surfaces prevent water from being evaporated into the atomsphere, therefore, net radiation in such surfaces will mostly be converted into ground and sensible heat. This is the main reason for the phenomenon of urban heat island enlargement. Here, we use the indictor of *NDTI* to analyse the change in thermal environment. *NDTI* profiles along the cross section of AA′ shows an evident increase (Fig. 3) in 2001 than that in 1987, illustrating the significant enlargement of urban heat island. Along the AA′ line, the *NDTI* is mostly about 0.4 with the peak less than 0.6 in 1987; while, most part of the *NDTI* profile in 2001 is greater than 0.5 and the peak amounts to 0.65.

The influence of urbanization on water cycle

Another important impact of urbanization on environment is that urbanization strongly affects surface water balance and then affects other hydrological and meteorological factors.

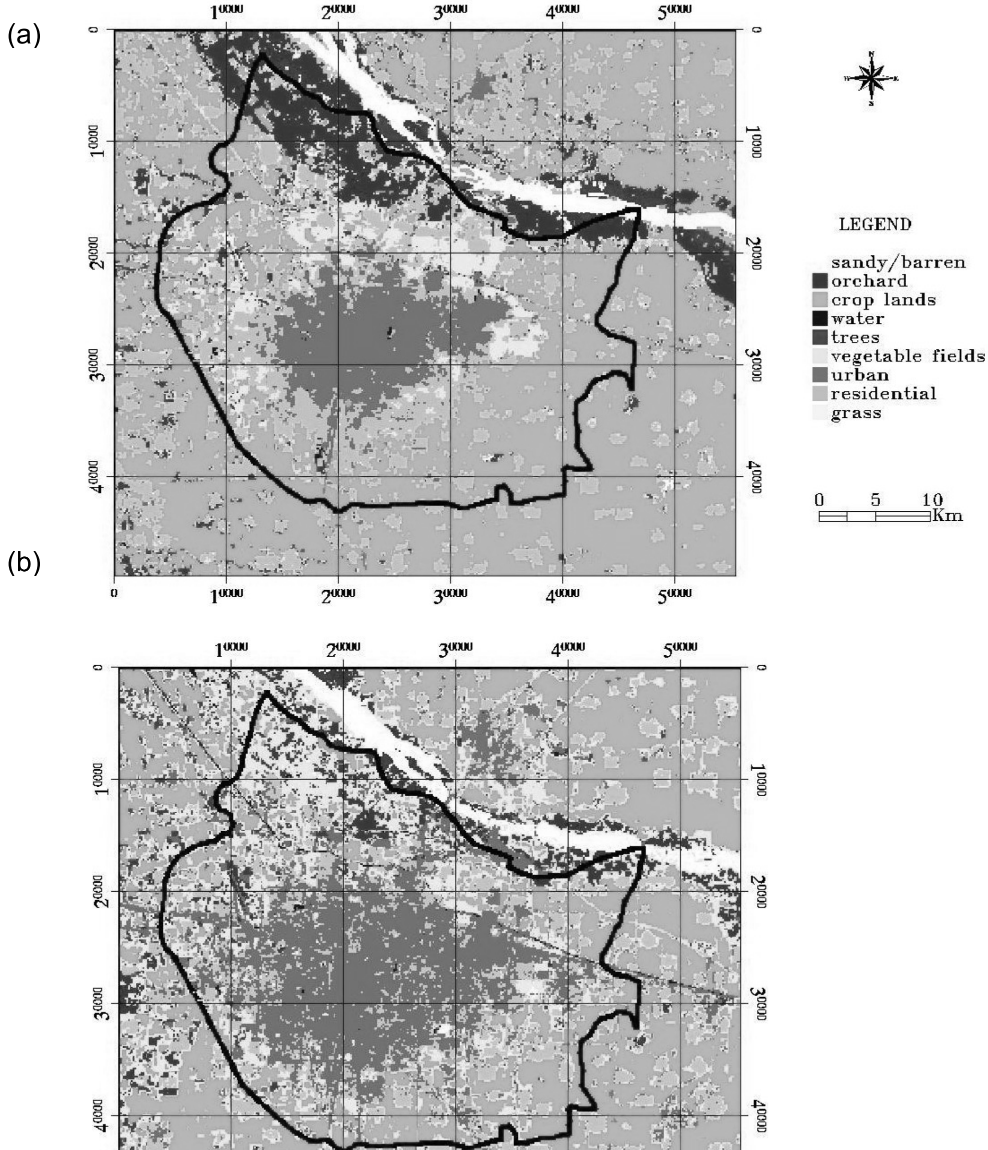

Fig. 1 The land use and land cover maps of Shijiazhuang in 1987 (a) and 2001 (b). (The line AA′ is a cross section for analysing the change in thermal environment.)

Table 1 The conversion matrix of land use types during 1987 to 2001 (unit: hectare).

2001 / 1987	Built-up	Fields	Forest	Others	Total
Built-up	12 327.91	1316.66	46.79	203.52	13 894.88
Fields	4744.57	10 927.57	588.15	321.17	16 581.46
Forest	537.84	1826.24	811.55	199.93	3375.56
Others	88.07	163.48	41.17	18.18	310.90
Total	17 698.39	14 233.95	1487.66	742.80	34 162.80
Change rate (%)	27.37	–14.16	–55.93	138.92	–

$$Change\ \ rate\ \ (\%) = \frac{\sum A_{2001} - \sum A_{1987}}{\sum A_{1987}} \times 100$$

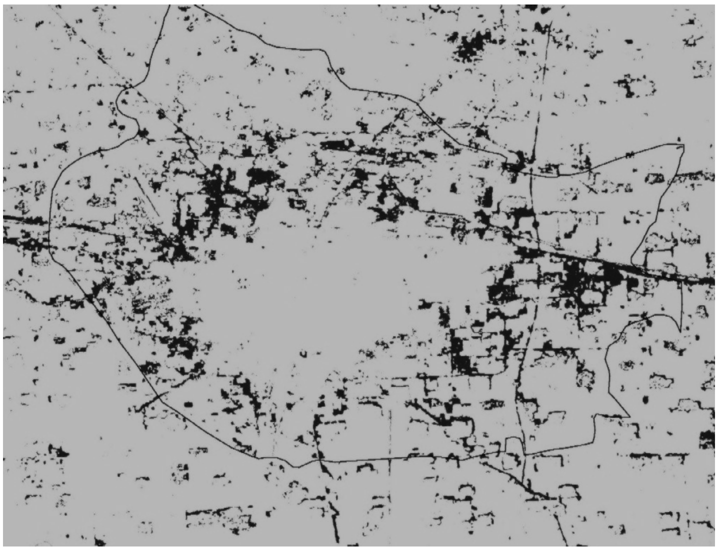

Fig. 2 The distribution of expanded built-up area during 1987–2001.

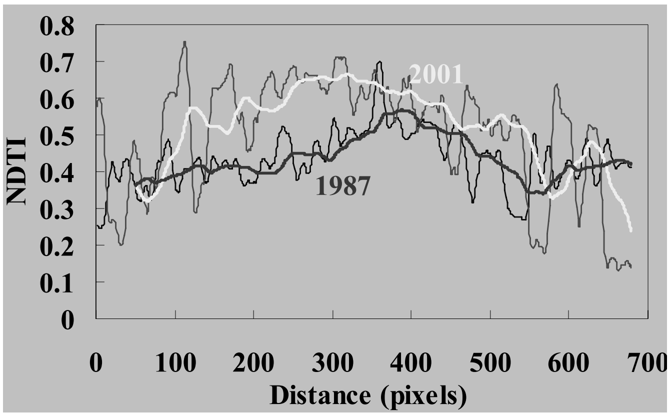

Fig. 3 Enlargement of urban heat island due to urbanization measured by NDTI.

Table 2 Comparison of the water balance change in the study area.

	P (mm)	*Irr* (mm)	*R* (mm)	*ET* (mm)
1985	447.4	250.7	201.9	496.2
1986	308.2	333.3	125.4	516.1
1987	312.9	330.5	127.3	516.1
1988	500.9	219.0	234.0	485.9
1989	449.9	249.2	203.4	495.7
1999	366.8	242.5	196.6	412.7
2000	453.5	200.7	256.0	398.2
2001	289.8	279.6	150.1	419.3
2002	397.0	228.0	216.9	408.1
2003	597.0	131.6	360.9	367.7
Avg1985–1989	403.9	276.5	178.4	502.0
Avg1999–2003	420.8	216.5	236.1	401.2
Change (%)	4.2	–21.7	32.3	–20.1

Table 2 compares water balance between the period of 1985–1989 and 1999–2003. The mean annual precipitation of these two periods is very close to each other. However, the mean runoff is increased by around 32% due to the increased built-up area (27.4%). ET was decreased about 20%, and as a result, the surface temperature increased to compensate for the excessive energy due to ET reduction. This result implies that urbanization increases the risk of urban floods during extreme rainfall events and contributes to enhance the heat island.

In addition, fast urbanization can quickly increase the municipal water demand and consumption and lead to a higher pressure on the water supply, especially in semiarid or arid regions. Our field study illustrates that urbanization in the Shijiazhuang area largely changed the water cycle by disturbing the natural structure of recharge and discharge in the groundwater system (Shen *et al*., 2005). The increasing water demand of Shijiazhuang due to urban enlargement in the last 70 years led to a significant decrease of groundwater table and land subsidence. Large quantities of drainage wastewater are pumped directly onto cropped fields every year, which has also caused groundwater pollution (Tang *et al*., 2003).

DISCUSSION

Assessing the influence of urbanization on hydrological environment is very complicated. Here, we only give the preliminary results on the analysis of thermal environment and water balance. Urbanization in China tends to a trend of spreading to the outreach of the old city area. Thus the continuous area of impervious surface is significantly enlarged and the land surface properties such as reflectivity and thermal capacity are also largely changed. These changes directly affect the energy balance of the land surface. One impact is the reduction of the energy partitioning to latent heat and the resulting increase of the sensible heat, which directly influences the surface temperature and consequently the air temperature, resulting in the enlargement of the urban heat island.

However, the increase of impervious surface can prevent the rainwater infiltrating into soil and generating more surface runoff. This can increase the pressure on the city drainage system and the risk of urban flood. In the case of Shijiazhuang, the results show the surface runoff can increase 32% annually and evapotranspiration can decrease by 20%.

In this present paper we only analysed the physical aspects of the impacts due to urbanization. The impacts of urbanization on chemical aspects of the local environmental system are more important. Comprehensive investigations on both the physical and chemical aspects of the impacts of urbanization on hydrological systems are encouraged to enhance our understanding of the environmental system, especially under the scenarios of climate warming and rapid economic development.

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