THE LONG-TERM HYDROLOGICAL IMPACT ASSESSMENT OF LAND USE AND LAND COVER CHANGES USING L-THIA MODEL IN THE QINHUAI RIVER WATERSHED OF JIANGSU PROVINCE, CHINA

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ABSTRACT

This study examined the effects of land use and land cover changes due to urbanization on the annual direct runoff of the Qinhuai River Watershed in Jiangsu Province, China. Landsat Thematic Mapper (TM) images from 1988, 1994, 2006, Enhanced Thematic Mapper Plus (ETM+) images from 2001 and 2003, and China-Brazil Earth Resources Satellite (CBERS) image from 2009 were used to obtain historical land use and land cover maps. These maps revealed that the watershed experienced conversion of approximately 16% non-urban area to urban area between 1988 and 2009. The Long-Term Hydrological Impact Assessment (L-THIA) model was used to calculate direct runoff generation. The model was calibrated and validated using observed daily stream flow data collected at the outlets of the watershed, and then repeatedly run with different urbanization scenarios to investigate the hydrological response to land use changes. The simulation results of L-THIA model for the various urbanization scenarios indicate that when the impervious surface area changed from 3.4% of 1988 scenario to 20.5% of 2009 scenario, the average annual direct runoff depth would increase from 355 mm to 496 mm. The results also indicate that the annual direct runoff depth is highly correlated with the percentage of impervious surface area. When impervious surface area is less than 9.0%, the annual direct runoff depth will increase linearly with impervious surface area (R^2=0.97); however, when impervious surface area is greater than 9.0%, the annual direct runoff depth will also increase linearly with impervious surface area (R^2 = 1.00) but at much lower rate.

KEYWORDS: L-THIA, land use and land cover change, annual runoff

INTRODUCTION

Land use and land cover (LULC) change has a significant impact on water resources. At a watershed scale, LULC change due to urbanization can increase runoff, flooding, and nonpoint source pollution and can degrade downstream water bodies (Hollis, 1975; Weng, 2001; Li and Wang, 2009; Doughertyet *et al*., 2006; Du *et al*., 2012). Thus it is important to assess the potential hydrologic impacts of LULC change prior to watershed development (Bhaduri, *et al*, 2001).

To evaluate the hydrologic impacts of LULC change at a watershed scale, many hydrological models have been developed, such as the Technical Release 55 (TR-55) (NRCS, 1986), Storm Water Management Model (SWMM) (Huber *et al*., 1988), and Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), Cell Based Long Term Hydrological Model (CELTHYM) (Choi *et al*., 2003), and Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) (USACE-HEC, 2008). To assess the long-term impacts of LULC changes on the hydrology of a watershed, some of these models mentioned above require many types of data inputs and parameter estimation that are usually not readily available for land-use planners (Li and Wang, 2009; Sun *et al*., 2011). Therefore, it is necessary to develop a much easier-to-use model to evaluate hydrological effects of the LULC changes at a watershed scale. The Long-Term Hydrologic Impact Assessment (L-THIA) model is developed by Purdue University and the U.S. Environmental Protection Agency as a tool to assess how LULC change affects annual average runoff in a watershed. The model uses only readily available data, such as daily rainfall, land uses, and hydrologic soil group (Harbor, 1994; Lim *et al*., 2006). Because of its simplicity and effectiveness, the model has been widely used for long-term hydrological assessment (Harbor, 1994; Bhaduri, *et al*., 2000; Bhaduri, *et al.*, 2001; Lim *et al*., 2006; Li and Wang, 2009; Sun *et al*., 2011).

The objectives of this paper are: 1) to derive LULC classification maps of the study area; 2) to quantitatively assess the effects of LULC change on direct runoff using the L-THIA model; and 3) to investigate the relationship between annual direct runoff depth and increasing impervious surface area.

STUDY AREA AND DATA SETS

Study Area

The Qinhuai River Basin is located between 118°39' to 119°19' E longitude and 31°34' to 32°10' N latitude . It has an area of 2631 square kilometers, and the elevations range from 0 m to 417 m. The study area lies in the humid climatic region. The annual mean precipitation is approximately 1047 mm, and the annual mean temperature is about 15.4° C. The basin has experienced dramatic urbanization in the past decade, resulting extensive land use changes. Therefore, it is important to assess hydrologic response to land use changes for future land use planning and management purposes.

There are seven raingauge stations within or close to the watershed and two streamflow gauging stations at the outlets of the basin. Figure 1 shows the location of the study area in Jiangsu Province of China, the locations of the streamflow and raingauge stations, and the elevations of the watershed (Du *et al*., 2013).

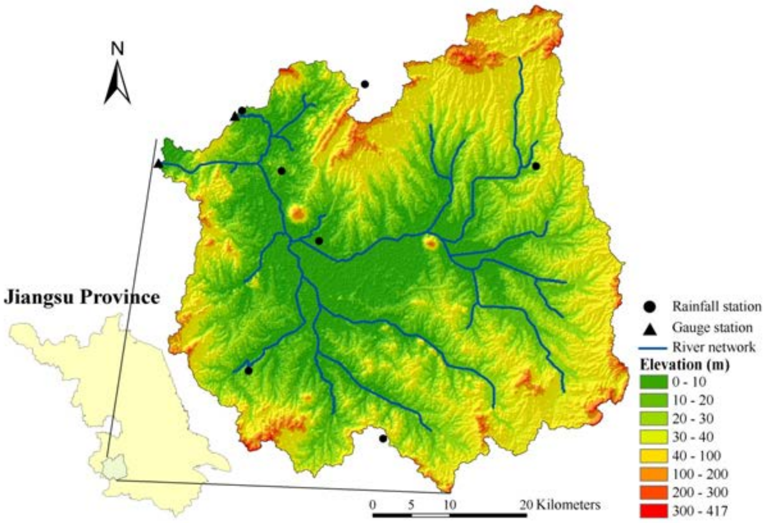

Figure 1. Map of Qinhuai River Basin study area.

Data Sets

The major data sets for L-THIA model include hydrological and climate data, soil data, and land use and land cover data. The following data sets were prepared for the input of the model: (a) 30-meter resolution Landsat Thematic Mapper (TM) images from 1988, 1994, and 2006, Enhanced Thematic Mapper Plus (ETM+) images from 2001 and 2003, and 20-meter resolution China-Brazil Earth Resources Satellite (CBERS) image from 2009; (b) a 1:75,000-scale digital soil map with the physical soil layer properties collected from Jiangsu Soil Handbook and field observations; (c) daily rainfall data at the seven raingauge stations that covers the period from January 1986 to December 2006; (d) daily discharge data at two gauging stations that covers the same period; (e) Digital Elevation Model (DEM) of the Qinhuai River Basin as auxiliary data for deriving LULC maps.

Supervised classification method with Maximum Likelihood Clustering, along with DEM data, was employed for image classification (i.e., a hybrid method) to generate a series of LULC maps. The selected

LULC maps are shown in Figure 2 and LULC changes are provided in Table 1. The detailed land use derivation process can be found in the literature of Du *et al*. (2012).

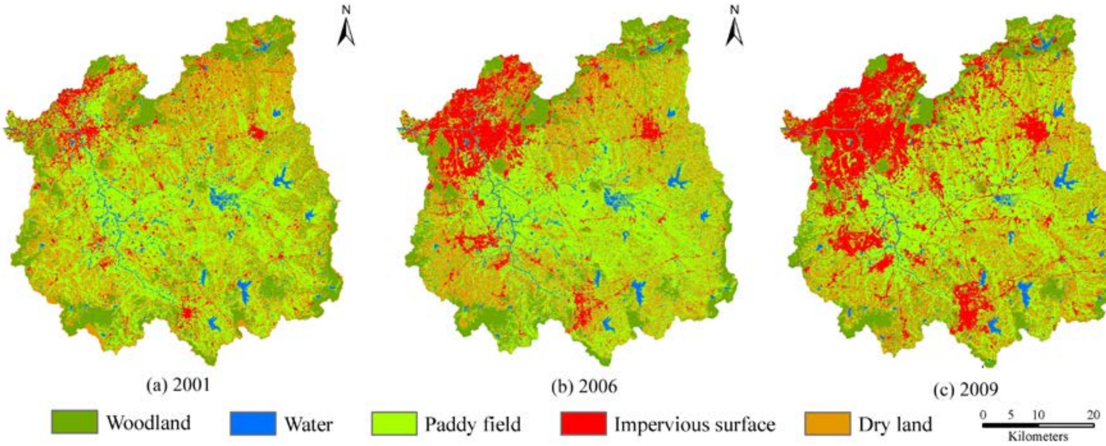

Figure 2. LULC maps of Qinhuai River Basin

From Table 1, it can be seen that paddy field and dry land decreased and impervious surface increased during 1988–2009. The rates of decrease and increase were increasing from 2003 to 2009.

Table 1. Land use types of the Qinhuai River Basin from 1988 to 2009 (in %)

Year	Impervious surface	Paddy field	Water	Woodland	Dry land
1988	3.4	47.8	4.0	18.5	26.3
1994	4.7	47.7	4.0	17.3	26.9
2001	6.6	45.0	4.2	17.5	26.7
2003	7.6	43.9	4.1	17.9	26.5
2006	12.1	41.6	4.0	17.2	25.1
2009	19.8	40.1	3.4	15.1	21.6

The digital soil data were classified into several categories, including yellow-brown soil, purple soil, limestone soil, paddy soil, and gray fluvo-aqvic soil (Figure 3). They were reclassified into hydrologic soil groups B (paddy soil, and purple soil) and C (yellow-brown soil, limestone soil, and gray fluvo-aqvic soil), according to rules of hydrologic groups classification for the L-THIA application (Figure 4).

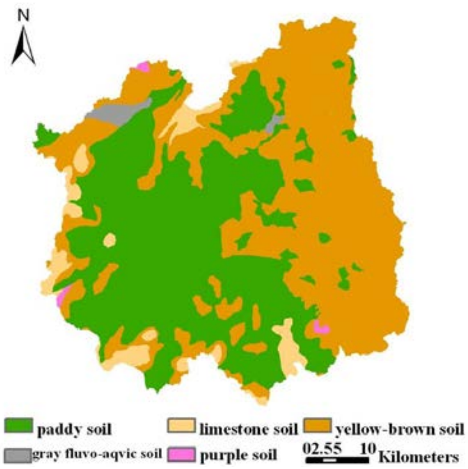

Figure3. The soil map

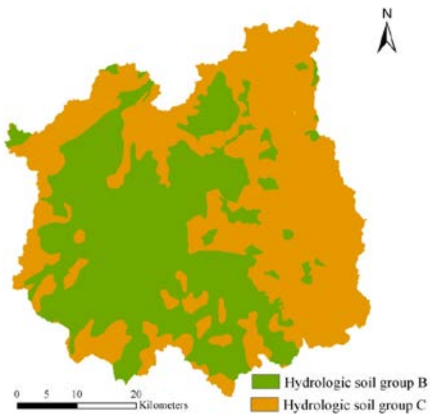

Figure 4. The hydrological soil groups.

METHODOLOGY

L-THIA Model Description

The L-THIA model uses the US Department of Agriculture (USDA) Natural Resources Conservation Service's curve number (CN) method with data inputs from daily rainfall, LULC, and hydrologic soil group data to calculate direct runoff (Harbor, 1994; Harbor *et al.*, 1998; Wang *et al.*, 2005; Sun *et al.*, 2011). The CN method uses the following equation to calculate direct runoff:

$$R = \frac{(P - I_a)^2}{P - I_a + S} \quad (1)$$

Where, R is direct runoff, P is the rainfall, I_a is the initial abstraction (initial loss), and S is potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation.

Based on the analysis of the results from many small experimental watersheds, the SCS developed an empirical relationship between I_a and S as $I_a = 0.2S$. Therefore, the direct runoff is given as:

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

The maximum retention (S) is determined using the following equation (SI system):

$$S = \frac{25400 - 254\text{CN}}{\text{CN}} \quad (3)$$

Where, CN is the curve number, which is an index that represents the combination of hydrologic soil group, land use classes, and antecedent moisture conditions. The values of CN can be obtained for different land uses, soil groups, and antecedent hydrologic conditions from the standard table provided by SCS-USA (NRCS, 1986).

As illustrated in Equations (2)-(3), L-THIA model requires long-term data sets such as daily precipitation data, soil data, and LULC data (Sun *et al.*, 2011). The output from the L-THIA model calculation is the mean annual total surface runoff in terms of depth and volume (Wang *et al*., 2005).

Calibration of L-THIA

In the L-THIA model, default CN values are used based on the land uses and hydrologic soil group combinations. However, CN values vary a lot due to different combinations of land uses, hydrologic soil groups, hydrologic conditions, cover types, and management practices (NRCS, 1986). The detailed classifications are not readily taken into consideration in the L-THIA model for direct runoff calculation, therefore, there is a need to calibrate CN values for better match with the measured direct runoff (Lim *et al*., 2006). In this study, the annual runoff depth was used as sole indicator to perform the calibration of CN values. The manual try-and-error method was used for the calibration based on default CN values provided by the L-THIA system and other study results in the area (Du *et al*., 2013)

Hydrological Assessment of LULC Impact

After the calibration, the L-THIA model was used to estimate annual direct runoff using daily rainfall data for the period of 1986 - 2006 with different LULC maps of 1988, 1994, 2001, 2003, 2006, and 2009. In order to analyze hydrological effects of urbanization, the urbanization scenarios were built by overlaying each impervious surface of 1994, 2001, 2003, 2006, 2009 to the land use map of 1988, producing urbanization scenarios for 1994, 2001, 2003, 2006, 2009 respectively. That way, the hydrologic effect of urbanization could be assessed, avoiding the effects caused by all other land use changes. The changes in direct runoff with different urbanization scenarios were analyzed, and the relationship between annual direct runoff and the impervious surface area was investigated.

RESULTS AND ANALYSIS

The Model Calibration

For model calibration, the land use map of 1988 and daily rainfall data for 1986-1990 were used for 1986-1990 simulation; the land use data for 1994 and daily rainfall data for 1991-1995 were used for 1991-1995 simulation; and the land use data for 2001 and daily rainfall data for 1996-2001 were used for 1996-2001 simulation. The calibrated CN values were listed in Table 2. The simulated annual direct runoff for 1988-2001 is 368 mm, which is 7.3 percent more than the observed annual runoff.

Table 2. The calibrated CN values.

Land use type / Hydrologic soil group	Impervious surface	Water	Dry land	Woodland	Paddy field
B	84	95	56	43	59
C	88	95	62	50	66

Direct Runoff in Response to LULC

Long-term simulation was conducted to estimate the impact of LULC change (predominant urbanization) on annual direct runoff under the same rainfall conditions for 1986-2006. L-THIA was run with the same CN values for urbanization scenarios of 1988, 1994, 2001, 2003, 2006, and 2009. Table 3 shows the simulated average annual direct runoff corresponding to urbanization scenarios.

Table 3. The simulated average annual direct runoff corresponding to urbanization scenarios

urbanization scenarios (year)	1988	1994	2001	2003	2006	2009
Annual direct runoff (mm)	355	376	410	425	459	496

Figure 5 shows average annual direct runoff percentage increase of 1994, 2001, 2003, 2006, and 2009 scenarios compared to 1988 pattern. From the Figure 5 we can see a runoff increase of 40% from 1988 to 2009. The runoff percentage increase was relatively low from 1988 to 2003 and was much higher in the 2006 and 2009 scenario.

Figure 6 shows the relationship between average annual direct runoff percentage increase and the percentage of impervious surface area. Strong and positive binomial relationships (R^2 = 0.99) were observed between runoff percentage increase and impervious surface area, though there was a good logistic relationship between them (R^2 = 0.97)(Figure 7), but linear relationships were more preferred, figure 8 shows that there was two types linear relationships between runoff percentage increase and impervious surface area, when impervious area is less than 9.0%, the direct runoff will increase linearly with the impervious area(R^2 = 0.97), however, when impervious area is great than 9.0%, the direct runoff will also increase linearly with the impervious area(R^2 = 1.00), but at much lower rate. The results indicated that the annual direct runoff increase was highly correlated with increasing impervious surface area, which is in agreement with those from Bhaduri *et al*. (2001) and Sun *et al*. (2011), who both applied L-THIA model to predict a linear relationship between average annual runoff and increasing imperviousness.

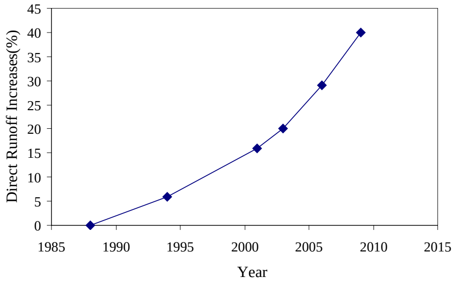

Figure 5 Average annual direct runoff increase of 1994, 2001, 2003, and 2006 compared to that of 1988.

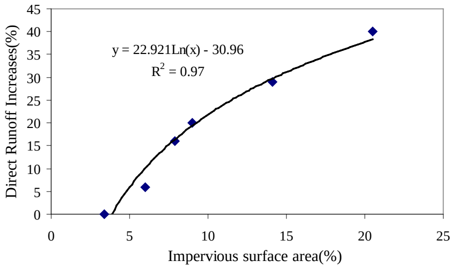

Figure 6. The logistic relationship between average annual direct runoff increase and the impervious surface area (%)

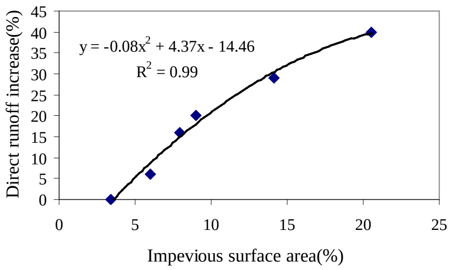

Figure 7. The binomial relationship between average annual direct runoff increase and the impervious surface area (%).

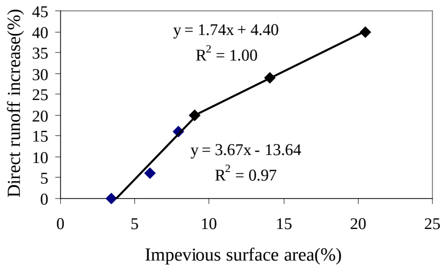

Figure 8. The linear relationship between average annual direct runoff increase and the impervious surface area (%) except 2006 pattern.

CONCLUSIONS

This paper presented a case study to investigate the long-term impacts of LULC changes on annual direct runoff in the fast urbanizing watershed of Qinhuai River, Jiangsu Province of China. The LULC maps were derived from Landsat TM/ETM+ and CBERS imagery acquired in 1988, 1994, 2001, 2003, 2006 and 2009 respectively using Supervised Maximum Likelihood Clustering method. An easy-to-use L-THIA model was applied to simulate direct runoff in the study area from 1986 to 2006. The long-term impacts of LULC changes (predominantly urbanization) on direct runoff were then assessed. The results indicated that the selected study area experienced rapid urbanization from 1986 to 2009, resulting in impervious surface areas increase from 3.4% in 1988 to 19.8% in 2009, while the paddy field decreased substantially from 47.8% in 1988 to 401% in 2009. The simulation of L-THIA model showed that the long-term average annual direct runoff would increased 40% when urbanization shifted from 1988 scenario to 2009 one. The results also indicated that the annual direct runoff increase was highly correlated with the percentage of impervious surface area. When impervious area is less than 9.0%, the direct runoff will increase linearly with the impervious area; however, when impervious area is greater than 9.0%, the direct runoff will also increase linearly with the impervious area, but at much lower rate. This research can provide a simple method for policy makers to assess potential hydrological impacts of the land use change for future planning and development activities.

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