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Urbanization dramatically altered the water balances of a paddy field-dominated basin in southern China

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Abstract. Rice paddy fields provide important ecosystem services (e.g., food production, water retention, carbon sequestration) to a large population globally. However, these benefits are diminishing as a result of rapid environmental and socioeconomic transformations, characterized by population growth, urbanization, and climate change in many Asian countries. This case study examined the responses of stream flow and watershed water balances to the decline of rice paddy fields due to urbanization in the Qinhuai River basin in southern China, where massive industrialization has occurred during the past 3 decades. We found that stream flow increased by 58 % and evapotranspiration (ET) decreased by 23 % during 1986–2013 as a result of a threefold increase in urban areas and a reduction of rice paddy fields by 27 %. Both high flows and low flows increased significantly by about 28 % from 2002 to 2013. The increases in stream flow were consistent with the decreases in ET and leaf area index monitored by independent remote sensing MODIS (Moderate Resolution Imaging Spectroradiometer) data. Attribution analysis, based on two empirical models, indicated that land-use/land-cover change contributed about 82–108 % of the observed increase in stream flow from $353 \pm 287\,\mathrm{mm\,yr^{-1}}$ during 1986–2002 to 556 ± 145 during 2003–2013. We concluded that the reduction in ET was largely attributed to the conversion of cropland to urban use. The effects of land-use change overwhelmed the effects of regional climate warming and climate variability. Converting traditional rice paddy fields to urban use dramatically altered land surface conditions from an artificial wetland-dominated landscape to an urban land-use- dominated one, and thus was considered an extreme type of contemporary hydrologic disturbance. The ongoing large-scale urbanization of the rice paddy-dominated regions, in humid southern China and East Asia, will likely elevate storm-flow volume, aggravate flood risks, and intensify urban heat island effects. Understanding the connection between land-use/land-cover change and changes in hydrological processes is essential for better management of urbanizing watersheds in the rice paddy-dominated landscape.

1 Introduction

Urbanization is a global phenomenon that poses profound threats to the local environment, society, and culture (Foley et al., 2005; McDonald et al., 2011). The most obvious direct consequence of urbanization is the altered hydrology and water balances that control the flows of energy and matter in watershed ecosystems (Paul and Meyer, 2001; Sun and Lockaby, 2012). In addition to the direct hydrologic impacts, indirect impacts of urbanization on local weather patterns (e.g., rainfall intensity and surface air temperature) are also becoming increasingly important in a changing climate (Yang et al., 2013).

It is widely known that urbanization elevates peak-flow rates (Brath et al., 2006; Du et al., 2012; Sun and Lockaby, 2012) as a result of increased impervious surfaces that promote quick surface runoff (Dietz and Clausen, 2008; Miller et al., 2014). However, the hydrologic response to urbanization is extremely variable (Jacobson, 2011; Caldwell et al., 2012), due to climatic differences and land-use change patterns across a watershed (Sun and Lockaby, 2012). Empirical data are still lacking information about changes in water balances and watershed hydrologic characteristics other than storm flow, such as total flow, low flow, and evapotranspiration (ET) (Dow and DeWalle, 2000; Boggs and Sun, 2011) in different physiographic settings (Barron et al., 2013). Previous studies rely heavily on simulation models (Kang et al., 1998; Kim et al., 2005, 2014; Sakaguchi et al., 2014). Controversies on the magnitude and underlying mechanisms of hydrologic responses to land conversion during urbanization remain in literature (Wang et al., 2009; He et al., 2009; Sun and Lockaby, 2012). In particular, data are scarce on the effects of converting paddy fields to other land uses, resulting in conflicting conclusions. For example, a simulation study in Taiwan suggested that rice paddy fields generated 55 % lower total runoff and 33 % lower peak flows than dry farms (Wu et al., 1997). However, another simulation study that used the HEC-HMS model for a rice paddy-dominated watershed in southern China found that an increase in impervious surface areas from 3 to 30 % increased the peak-flow rate and storm volume (4–20 %), but had a very limited impact on total annual flow (< 6 %) (Wang et al., 2009; Du et al., 2011, 2012) and thus long-term water balances.

The highly populated Yangtze River Delta (YRD) region covers about 2 % of China's land mass, but provides over 18 % of China's gross domestic product (Gu et al., 2011). The population increased by almost 13 % in the past decade to 156 million in 2013, and has become China's most industrialized region and one of the global "hot spots" of economic and social development. As the "home of fish and rice", southern China's landscapes have been dominated by rice paddy fields for thousands of years. The original coastal wetlands have long been ditched, drained, and cultivated for growing rice and other crops. Rice paddy fields are major sources of food production and offer many other ecosystem services similar to wetlands including flood retention, groundwater recharge (He et al., 2009), nutrient cycling, and sequestration of greenhouse gases (Tsai, 2002). One study on ten typical rice paddies in China concluded that their ecosystem service values exceed their economic values three-fold (Xiao et al., 2011). The rapid urbanization and population rise in a warming climate in the YRD region has caused serious environmental and resource concerns such as overdrawing and pollution of groundwater, flooding, land subsidence, and urban heat islands (UHIs) (He et al., 2007; Gu et al., 2011; Zhao et al., 2014). The majority of the existing studies on paddy fields have focused on grain yield and irrigation, with little research on the hydrologic response of paddy field-dominated landscapes to urbanization (Du et al., 2011, 2012; Kim et al., 2014).

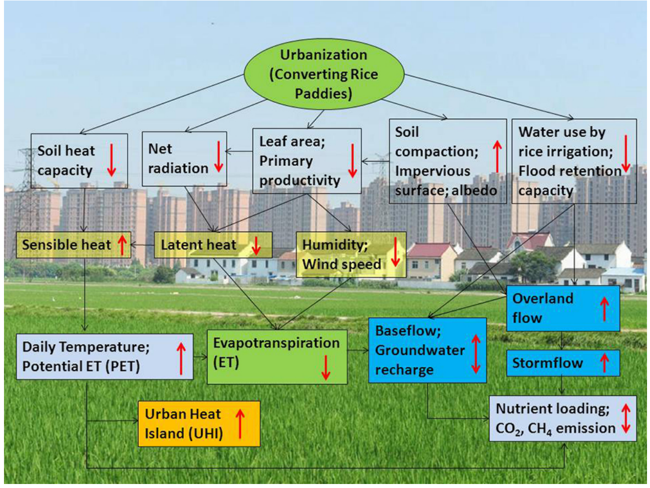

Figure 1. A conceptual model illustrating the potential hydrologic and environmental impacts of converting rice paddies to urban uses in the Yangtze River Delta region. Arrows represent directions (up or down or both) of change (background photo credit: http://blog.sciencenet.cn/blog-578415-712508.html).

Converting paddies to urban land use has had many ripple effects on the local environment (Fig. 1). In particular, because rice paddy fields are rarely under water stress, the water loss or actual ET is close to the potential ET (Wu et al., 1997) and has been recognized as their cooling functions in regulating local climate (Xiao et al., 2011). In contrast, urban land use is generally characterized by low vegetation coverage with low ET and high runoff (Sun and Lockaby, 2012).

A study on China's 32 cities by Zhou et al. (2014) concluded that UHI effects dropped more sharply from urban centers to the rural areas in humid southern China than in northern China or inland cities, indicating the stronger contrast of the energy regime in the paddy-dominated regions than in other regions.

Therefore, we hypothesized that converting rice paddy fields to urban areas represents the maximum ET reduction possible among all common land-cover change sce-

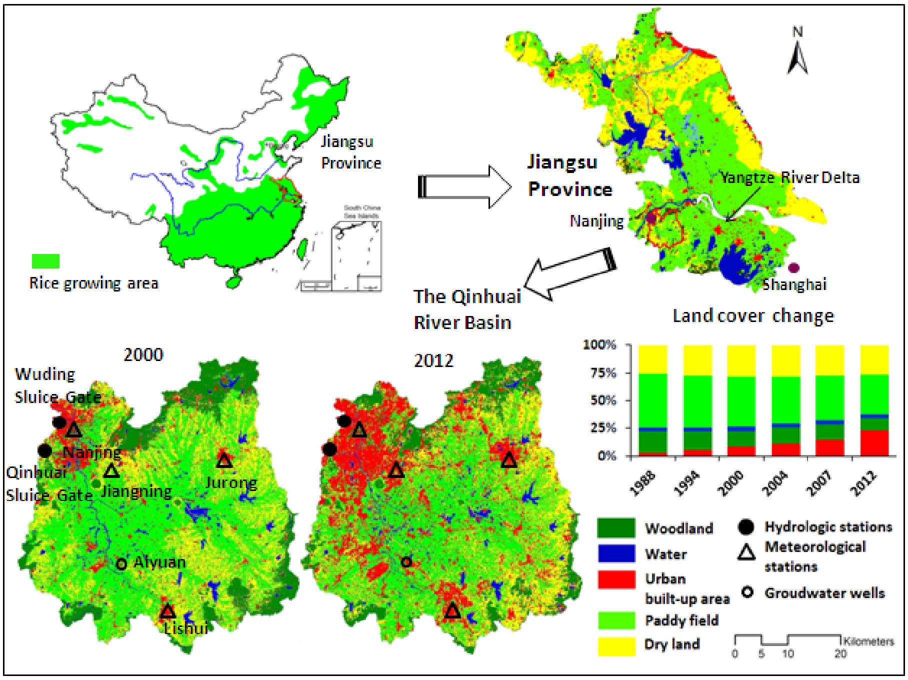

Figure 2. Watershed location, instrumentation, and land-use change patterns in the Qinhuai River basin, Yangtze River Delta in southern China. The insert map showing changes in land use derived from published data (Du et al., 2012; Chen and Du, 2014) (1988 and 1994) and Landsat 7 ETM+ images (2000–2012).

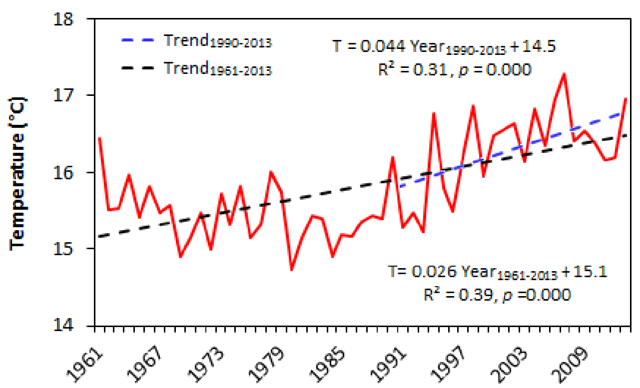

Figure 3. Mean annual air temperature change across four meteorological stations in the Qinhuai River basin in southern China during 1961–2013.

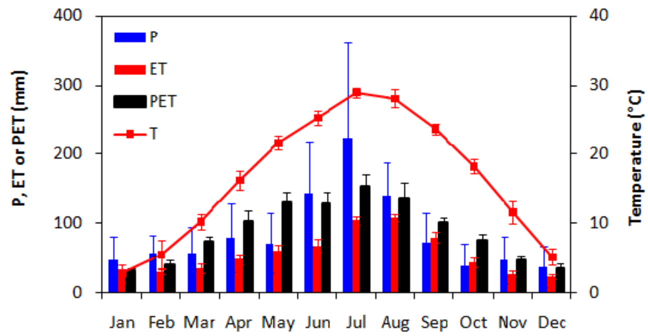

Figure 4. Mean monthly precipitation (P) (1986–2013), MODIS evapotranspiration (ET) (2000–2013), potential evapotranspiration (PET) (2000–2013) and temperature (T) (1986–2013). The vertical lines show standard deviation.

narios, potentially resulting in disproportionally higher impacts on water balances than other land conversion scenarios (e.g., converting dryland to urban uses). Along with the increase in impervious surface areas that are well known to increase storm flow, ET reduction during urbanization is likely to cause large impacts on the local micro-climate, stream flow, and water quality on paddy field-dominated watersheds (Fig. 1).

The overall goal of this study was to understand the processes underlining the hydrologic impacts of converting rice paddy fields to urban uses. The specific objectives of this study were: (1) to examine how urbanization in the past decade (2000–2013) has affected the water balances and hydrologic characteristics of the Qinhuai River basin (QRB), a typical landscape of the YRD (Fig. 2), (2) to test the hypothesis that urbanization in a paddy field-dominated watershed dramatically reduced ET, thus altered water balances, and (3) to explore the implications of urbanization for regional environmental change in southern China. In this study, we integrated long-term hydrometeorological monitoring data and remote sensing-based ET and vegetation products. Multiple advanced detection techniques were used to examine trends of climate and stream-flow overtime and their associations with biophysical variables, such as leaf area index and land-use dynamics.

2 Methods

2.1 The Qinhuai River basin (QRB)

As one of the tributaries of the Yangtze River, the QRB (31° 34′–32°10′ N, 118°39′–119°19′ E) has a catchment area of 2617 km^2. The QRB represents a typical landscape of the lower Yangtze River Delta region that is characterized by its flat topography with natural river networks which are severely modified, and land use which is dominated by paddy rice fields, dotted with small irrigation ponds that have been converted from natural wetlands over thousands of years (Fig. 2). As the "backyard garden" of Nanjing City, the capital of Jiangsu province, the QRB is gradually being recognized for its important ecosystem services in drought/flood prevention, crop irrigation, recreation, tourism, and emergency drinking water supply to over 8 million residents. The local climate is controlled by the East Asia summer monsoon (Gu et al., 2011). The multi-year mean air temperature is 15.4°C. Mean air temperature (1961–2013) across the study basin increased drastically by a rate of 0.44 °C $decade^{-1}$ from 1990 to 2013 (Fig. 3), suggesting an increasing trend in evaporative potential during the past 2 decades. The mean (1986–2013) annual precipitation is 1116 mm, with 75 % rainfall falling during April–October (Fig. 4). The observed long-term mean annual stream flow (per unit of area) is about 430 mm, concentrated from June to August. The QRB has seen rapid urbanization during the past decade. The urban built-up areas increased from 9 % (222km^2) to 12 % (301 km^2) from 2000 to 2004, but jumped to 23 % (612 km^2) in 2012, and the area of rice paddy fields decreased from 45 % (1188 km^2) of the total land area in 2000 to 43 % (1, 112 km^2) in 2004, and dramatically dropped to 36 % (932 km^2) in 2012 (Fig. 2). Documents by Jiangsu Province Rural Statistics reported that the total area of rice planting in the QRB shrank more than 25 % from 995 km^2 in 2000 to 745 km^2 in 2010.

2.2 Land use, climate, stream flow, potential ET, ET, and leaf area index (LAI)

We retrieved land-use and land-cover (LULC) data for four key time periods, 2000, 2004, 2007, and 2012, using Landsat TM and ETM+ images with a 30 m pixel resolution (http://glovis.usgs.gov/). We also compared our analysis to land-use and land-cover data acquired for the period from 1988 to 2012 from other multiple sources, including published theses and journal papers on the study basin (Du et al., 2012; Chen and Du, 2014). For land use in 2010, we also used the new Finer Resolution Observation and Monitoring of Global Land Cover that was created by Tsinghua University using Landsat TM and ETM+ data (Gong et al., 2013). The daily meteorological data (precipitation, radiation, temperature, wind speed, and humidity) for estimating potential ET were acquired from four standard climatic stations maintained by the local meteorological bureau across the QRB (Fig. 2). Stream-flow data with varying temporal resolutions were compiled from hydrologic records for two hydrological stations, the Wuding sluice gate (Wuding station thereafter) and the Inner Qinhuai sluice gate (Inner Qinhuai station thereafter), which controlled the outflows from the Qinhuai River and back flows from the Yangtze River (Fig. 2). The daily stream-flow data (2002–2003; 2006–2013) for the "flooding periods" from May to October recorded at the Wuding station were used to characterize high flows and low flows. The total annual stream flow discharged to the Yangtze River was the sum of flows measured at the Wuding station and the Inner Qinhuai station. Total annual stream-flow data for the period of 1986–2006 were reported in Du et al. (2011) and we collected daily and monthly stream-flow data for other periods (Table 1).

Potential ET (PET) represents the maximum ecosystem evapotranspiration when soil water is not limited, such as for the case of paddy fields. PET represents a comprehensive index of availability of atmospheric evaporative energy that is controlled by radiation, temperature, humidity, and wind speed. Daily PET rates were calculated using the standard FAO 56 method and were averaged across the four climatic stations for the period 2000–2013 (Allen et al., 1994). The improved MOD16 data sets provide consistent estimates of global actual ET at an 8-day and 1 km^2 resolution (Mu et al., 2011). Yuan et al. (2011) reprocessed the MODIS leaf area index (LAI) data sets using the modified temporal spatial filter (mTSF) and time-series analysis with the TIMESAT software (Jonsson and Eklundh, 2004) and provided reliable continuous LAI estimates from 2000 to 2013. Mean monthly PET and MODIS ET rates are presented in Fig. 4 along with other climatic variables to contrast seasonal ET, PET, and P that controlled seasonal stream flow.

2.3 Change detection

Three statistical methods were used to comprehensively examine the temporal changes in the long-term hydro-climatic data series: (1) the Mann–Kendall test (Mann, 1945; Kendall, 1975) for the non-linear trend at significance levels of $\alpha = 0.001$, 0.01, 0.05, and 0.10, (2) Sen's nonparametric method, applied to examine the linear trend and to estimate the true slope of an existing trend as change per year (Gilbert, 1987), and (3) the dynamic harmonic regression (DHR) method, used for determining the change rates for meteorological, hydrological, and LAI time series based on the Captain Toolbox (Taylor et al., 2007). The DHR model was used to fit three main components in a time series including the trend of the original time series, the periodicity, and

Table 1. A summary of land use, climate, and hydrology data resources.

Data type	Data resources	Data details	Periods	Spatio-temporal resolution
Land use/land cover	Landsat TM and ETM+ images (http://glovis.usgs.gov/) published theses and journal papers; Du et al. (2012); Chen and Du (2014); Gong et al. (2013)	Land-use/land-cover types	1988, 1994, 2000, 2004, 2007 and 2012	30 m
Climate	Jiangsu meteorological bureau (four meteorological stations)	Precipitation, radiation, temperature, wind speed, and humidity	1961–2013	Daily
Stream flow	Two hydrological stations: the Wuding sluice gate and the Inner Qinhuai sluice gate. Published journal papers; Du et al. (2011)	Stream flow	2002–2003 (May–October), 2006–2013 (May–October), 1986–2006	Daily (2002–2003, 2006–2013); Annual (1986–2006)
Groundwater	Aiyuan well station	Groundwater table depth	2006–2013	Monthly
Actual ET	Improved MOD16 data sets Mu et al. (2011)	Actual ET	2000–2013	8-day and 1 km^2 resolution
Leaf area index (LAI)	Improved MODIS LAI data sets (http://globalchange bnu.edu.cn/research/lai) Yuan et al. (2011)	LAI	2000–2013	8-day and 1 km^2 resolution

the residuals, which were referred to as Gaussian white noise for convenience. The key feature of the DHR model is its ability to characterize the seasonal or periodic components of time series data, so the method is suitable for analyzing time series with remarkable seasonal variations. The DHR model analyzes the seasonal or periodic component using a similar approach to Fourier analysis.

We used a series of common hydrologic detection methods to determine magnitude and timing of the effects of land-use change and climate change on stream flow (Ma et al., 2010; Tang et al., 2011; Wei and Zhang, 2010). The flow duration curve (FDC) (Vogel and Fennessey, 1993) and the double mass curve (DMC) methods (Wei and Zhang, 2010) were used to determine changes of stream-flow frequency in daily and annual stream flow, respectively, as a result of urbanization.

The trend of the base-flow component of the stream flow is one important indicator of change in soil water storage, i.e., soil moisture and groundwater conditions (Price et al., 2011). The base-flow index (BFI) program was used to separate the base flow from measured total daily stream flow (Wahl and Wahl, 1995). Our results showed that N, the number of days over which a minimum flow could be determined, was 7 days for the study basin (Fig. 5), suggesting that BFI (base-flow : stream-flow ratio) would not change to much shorter than 7 days. We used a value of 0.9 for the turning point factor (f) to remove daily stream flow greater than 100 m^3 s^{-1}. Details of the methods to determine N and f can be found in Wahl and Wahl (1995).

2.4 Attribution analysis

Once the hydrologic change point was detected, we determined the individual contributions of climate and land-cover/land-use change to the observed stream-flow change. We assumed that the observed stream-flow change (ΔQ) in the study basin could be explained by the sum of change in climate (ΔQ_{clim}) and change in land use/land cover (i.e., urbanization) (ΔQ_{lulc}):

$$\Delta Q = \Delta Q_{\text{clim}} + \Delta Q_{\text{lulc}}.$$

Then, the contribution of land cover/land use ($\%\Delta Q$) can be estimated as

$$\%\Delta Q_{\text{lulc}} = (\Delta Q - \Delta Q_{\text{clim}}) / \Delta Q \cdot 100,$$
$$\text{or} \quad \%\Delta Q_{\text{lulc}} = (1 - \Delta Q_{\text{clim}} / \Delta Q) \cdot 100.$$

ΔQ represents the observed mean annual Q in the second period – Q in the reference period (i.e., $\overline{Q}_0$).

We used the climate elasticity model (CEM) and the rainfall–runoff model (RRM) to determine ΔQ_{clim} (Li et al., 2007). The CEM involved developing an empirical relationship between the deviation of Q (Q_{0i}) and deviations P (P_{0i}) and PET (PET_{0i}) from the long-term means for the reference period:

$$\frac{Q_{0i}}{\overline{Q}_0} = \alpha \cdot \frac{P_{0i}}{\overline{P}_0} + \beta \cdot \frac{\text{PET}_{0i}}{\overline{\text{PET}}_0},$$

where α and β were fitted "climate sensitivity" parameters derived from annual climate data for the reference period (1986–2002) in this study, as determined by the double mass

Table 2. The conversion matrix for land-use change during 2000–2012 in the Qinhuai River basin.

2000 (km^2)	2012 (km^2)					
	Dry crop lands	Paddy fields	Forest	Water	Urban built-up areas	$\sum$
Dry crop lands	320	226	7	8	175	736
Paddy fields	257	681	6	24	220	1188
Forest	74	2	264	2	24	366
Water	16	12	2	59	14	104
Urban built-up areas	26	13	3	3	178	223
$\sum$	693	933	283	96	611	2617
Area change from 2000 to 2012 (km^2)	−43	−255	−83	−8	388	–
Area change from 2000 to 2012 (%)	−6	−21	−23	−8	174	–

Table 3. Summary of Z statistics by the Nonparametric Mann-Kendall trend tests for temperature (T), ET, PET, precipitation (P), and LAI during the periods of July–August, April–October, and annual, Qinhuai River basin (2000–2013).

Periods	Z statistic				
	LAI(s)	ET(s) (mm)	PET(s) (mm)	P(s) (mm)	T(s) (°C)
July–August	−2.41* (−0.04)	−2.3* (−1.7)	1.3 (2.4)	1.31 (12.9)	1.31 (0.07)
April–October	−2.30* (−0.02)	−1.2 (−2.4)	2.4* (5.1)	0.11 (2.6)	0.77 (0.02)
Annual	−2.08* (−0.01)	−1.5 (−3.6)	2.5* (7.5)	−0.55 (−8.0)	0.00 (−0.00)

* Denotes significance level of 0.05.
"s" is the true slope of the linear trend, i.e., change per year.

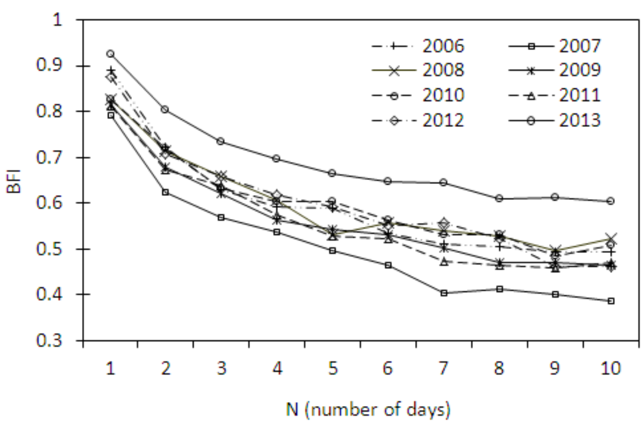

Figure 5. Sensitivity of base-flow index (BFI) to the number of days (N) used to select the minimum value in base-flow separation analysis from 2006 to 2013 at the Wuding station located at the outlet of the Qinhuai River basin.

method while $\overline{Q}_0$ and $\overline{P}_0$ represented mean measured annual stream flow and precipitation. $\overline{\mathrm{PET}}_0$ represents mean annual potential ET estimated by the FAO reference ET method (Allen et al., 1994). Then, the effects of climate change in the second period in question could be calculated as

$$\Delta\overline{Q}_{\mathrm{clim}} = \overline{Q}_{\mathrm{pre}} - \overline{Q}_0,$$

where $\Delta\overline{Q}_{\mathrm{clim}}$ represents the mean effects of climate change on annual stream flow during the second period, $\overline{Q}_{\mathrm{pre}}$ predicts mean stream flow using the climate (P and PET) for the second period and the empirical equation developed from the reference period, and $\overline{Q}_0$ represents observed stream flow during the reference period, respectively.

The second method rainfall–runoff model (RRM) was chosen to strengthen the attribution analysis by considering the seasonal climatic variability. This method involved developing the relationships between Q, P, and the variances (σ_{0i}^2) of P calculated using monthly P data series without consideration of PET (Jones et al, 2006; Li et al., 2007):

$$Q_{0i} = a + bP_{0i}(\sigma_{0i}^2)^c,$$

where Q_{0i} and P_{0i} are the annual Q and P for the reference period, respectively, while σ_1^2 is the variance of the monthly P. The values of the three parameters, a, b, and c were derived using data from the reference period. The empirical model was then applied to estimate annual stream flow using precipitation for the second period (Q_{pre}) and finally to calculate the mean changes in Q ($\Delta\overline{Q}_{\mathrm{clim}}$) as the differences between $\overline{Q}_{\mathrm{pre}}$ and mean stream flow for the reference period ($\overline{Q}_0$).

Table 4. Modeled contributions of land-use change and climate change to the increase in stream flow (mm yr^{-1}) by the climate elasticity model (CEM) and rainfall–runoff model (RRM).

Period	$\overline{P}$	$\overline{PET}$	$\overline{Q}$	ΔQ_0	CEM ($\alpha = 0.27$; $\beta = -0.65$)		RRM ($a = -509$; $b = 0.45$; $c = 0.064$)	
					$\Delta\overline{Q}_{clim}$	$\Delta\overline{Q}_{lulc}$	$\Delta\overline{Q}_{clim}$	$\Delta\overline{Q}_{lulc}$
1986–2002 (reference)	1105 ± 291	998 ± 82	353 ± 287	–				
2003–2013	1134 ± 178	1075 ± 45	556 ± 145	203	-15 ± 23	218 ± 131 (108 %)	36 ± 169	167 ± 100

3 Results

3.1 Land conversion and change in LAI

During 2000–2012, the QRB went through dramatic land-cover changes characterized by an increase in urban areas and a decrease in paddy fields (Du et al., 2011, 2012; Chen and Du, 2014) (Fig. 2). The land-cover change matrix shows that, from 2000 to 2012, the area of urban built-up areas increased 388 km^2 or 174 % at the expense of dry crop lands (decreased 43 km^2, or 6 %), paddy fields (decreased 255 km^2, or 21 %), and forest lands (decreased 83 km^2, or 23 %) (Table 2). Since dryland changed relatively slightly from 2000 to 2012 (Fig. 2 and Table 2), the majority of detected reduction in cropland area came from the changes in paddy fields.

MODIS data indicated that both mean annual and peak growing season watershed level LAI decreased significantly ($p < 0.05$) with Z statistic of -2.08 and Z statistic of -2.41, respectively (Table 3) (Fig. 6). Since the major decrease in land use was paddy rice, the decline of LAI was mainly caused by land conversion of paddy field to urban uses. The decrease trend of LAI followed a similar pattern as ET during 2000–2013.

3.2 Trend in climate and MODIS ET

The M–K test showed that the growing season precipitation had a weak increasing trend, but annual total precipitation had an insignificant decreasing trend during 2000–2013 (Table 3). The mean annual air temperature showed an insignificant change, but with an weak increase of 0.07° C yr^{-1} in the peak growing season from July to August (Table 3). Both annual and growing season PET rose significantly by 7.5 mm yr^{-1} (Z statistic 2.5, $p < 0.05$) and 5.1 mm yr^{-1} (Z statistic 2.4, $p < 0.05$), respectively, an opposite trend of the actual ET (Table 3). The DHR method also identified a rising trend for annual PET.

The mean annual MODIS ET was 655 mm yr^{-1}, varying from a low of 598 mm yr^{-1} in 2011 to the highest 715 mm yr^{-1} in 2002 during the study period (2000–2013). Annual ET exhibited a general decreasing trend (-3.6 mm yr^{-1}) and pronounced decreases in the peak growing season of July to August (-1.7 mm yr^{-1}, Z statistic -2.3, $p < 0.05$) (Table 3) (Fig. 4). The ET linear trend during the peak growing season (July–August) accounted for

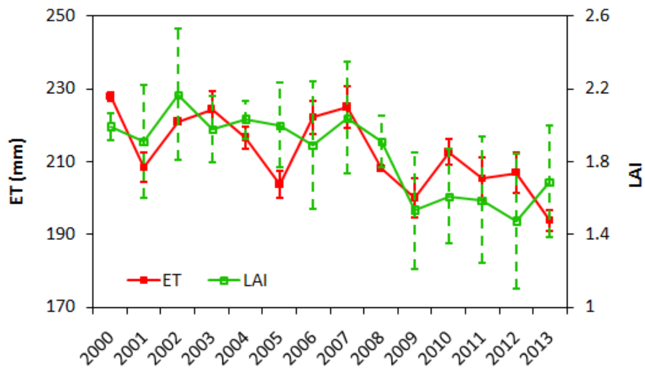

Figure 6. Total MODIS ET (mm per 2 months) and mean LAI during the peak growing season (July–August) over 2000–2013 in the Qinhuai River basin. Vertical lines represent standard deviation across space.

32 % of the total annual trend. Overall, ET showed a similar decreasing trend to LAI in the peak growing season during 2000–2013 (Fig. 6). Annual ET and the peak growing season ET departures from the long-term means had significantly positive correlations with LAI departures ($R = 0.46$, $p = 0.1$; $R = 0.64$, $p = 0.015$, respectively), but weak negative correlations with PET departures ($R = -0.38$, $p = 0.18$) during 2000–2013 (Fig. 7).

3.3 Changes in stream-flow characteristics

The FDC analysis for the flow measured at Wuding sluice gate indicated that both daily high flows and low flows were elevated during 2009–2013 compared to 2002–2008, with the median flow rates increased from 30 $m^3 s^{-1}$ to 38 $m^3 s^{-1}$ (Fig. 8). The extreme high flow in 2002–2008 was caused by one extreme rainfall event in July 2007 (rainfall was 339 mm) that resulted in widespread flooding. The base-flow analysis also showed a significant ($p = 0$) increasing trend during 2006–2013 (Fig. 9). The increase in base flow or low flow coincided with the observations that the groundwater levels in the study basin were on the rise in recent decades as a result of groundwater management and likely land-use change in recent decades (Fig. 10). The runoff coefficient (stream flow : precipitation ratio) during the May–October period (wet, flooding seasons) increased significantly from 0.32 to

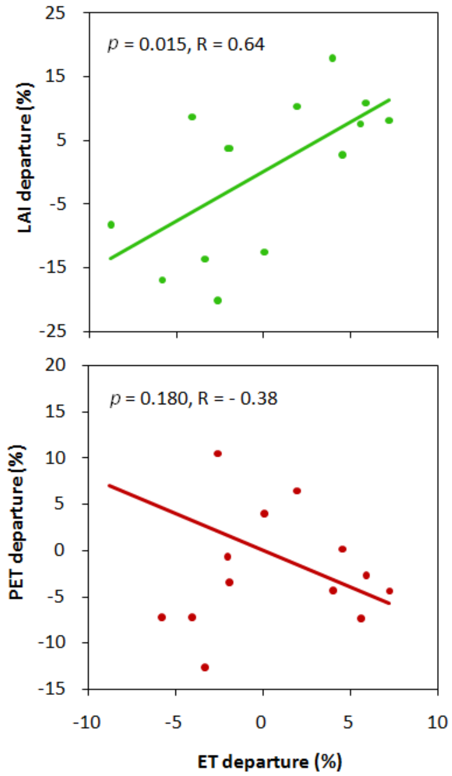

Figure 7. Correlations of the departures of basin-level ET with **(a)** the departures of mean leaf area index (LAI) and **(b)** the departures of PET in the peak growing season (July–August) over 2000–2013 in the Qinhuai River basin.

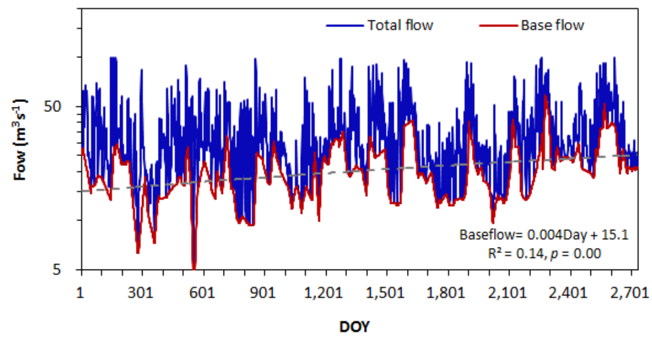

Figure 9. Trend of daily base flow separated from total stream flow measured at the Wuding station during 2006–2013. DOY (day of year) is the number of accumulated days since 1 January 2006.

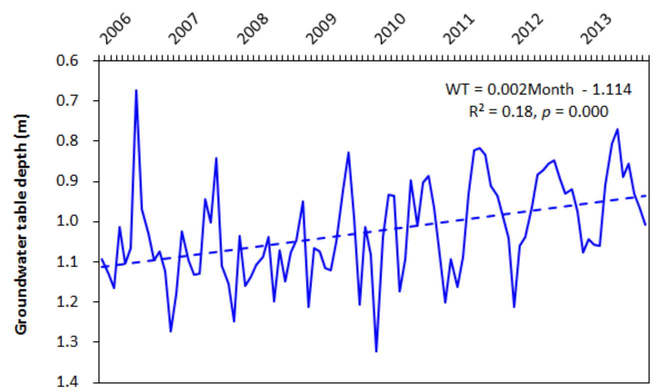

Figure 10. The trend of monthly groundwater table depth fluctuations measured at the Aiyuan well station in the Lishui subbasin during 2006–2013.

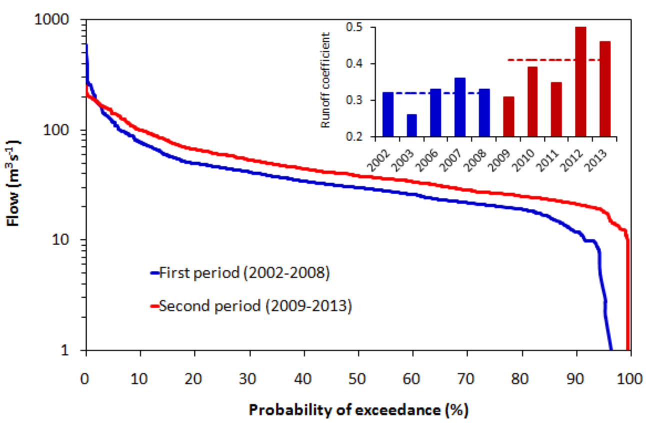

Figure 8. Flow duration curves for mean daily flow in the first period (2002–2003 and 2006–2008) and the second period (2009–2013) (May–October) measured at the Wuding station in the Qinhuai River basin. The insert shows the runoff coefficient, the ratio of stream flow/precipitation for the period from May to October when the flow control gate was open.

0.41, or 28 %, during 2002–2013 (Z statistic 2.89, $p < 0.01$) (Fig. 8).

3.4 Changes in annual watershed water balances

The DMC analysis identified a clear “break point” of total annual stream flow (Q) around 2003 (Fig. 11). The slopes of the regression lines between accumulated precipitation and stream flow increased from 0.27 to 0.50. Mean annual stream flow significantly increased from 353 mm to 556 mm from period 1 (1986–2002) to period 2 (2003–2013) (Fig. 12). This represents an increase in runoff coefficient (Q / P) from 0.32 to 0.49, a 53 % increase. The trend of annual stream flow was influenced heavily by the year 1991; a huge flooding event occurred in the Yangtze River basin. When this year was removed, R^2 increased from 0.1 to 0.34 and p value increased to a highly significant level ($p = 0.002$). In the meantime, annual ET as estimated by $P - Q$, decreased significantly from 752 mm to 578 mm from period 1 to period 2, representing a decline in ET by 23 % or an ET / P ratio of 25 %.

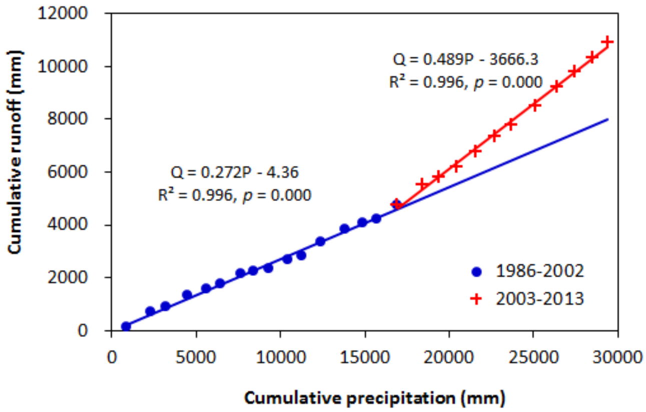

Figure 11. Double mass curves showing the relationships between accumulated annual precipitation (P) and total stream flow (Q) for the Qinhuai River basin (1986–2013). The extreme wet year of 1991 was removed from the analysis.

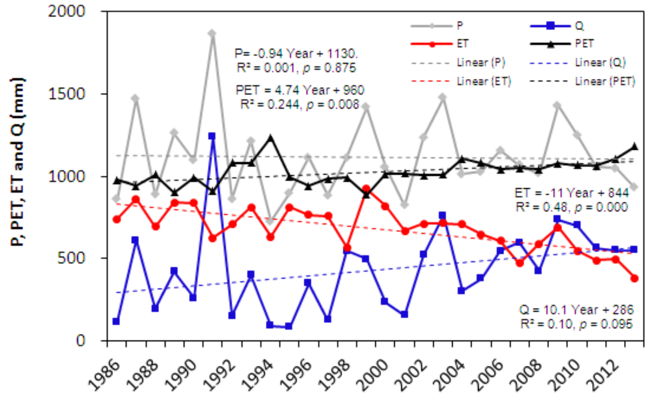

Figure 12. Trend of annual water balance and potential evapotranspiration (PET) for the Qinhuai River basin from 1986–2013. ET was estimated as the difference between precipitation (P) and measured stream flow (Q).

3.5 Contributions of LULC change and climate change and variability

The two models gave consistent results on the contributions of climate change ($\%\Delta Q_{\text{clim}}$) and LULC change ($\%\Delta Q_{\text{lulc}}$) to the observed annual increase (203 mm) in stream flow from the reference period of 1986–2002 to the evaluation period 2003–2013 (Table 4). The CEM model results suggested that the combinations of P and PET caused a decrease of stream flow and the contribution of climate was negative (−8 %). Thus the contribution of LULC was positive (108 %), more than 100 %. In contrast, the RR model that did not include PET as a climatic factor suggested P alone contributed 18 % to the increase of stream flow while LULC change contributed 82 %. The modeling results indicate that PET is an important factor in evaluating the impacts of climate and LULC change. Hydrologic change in the study basin was controlled by both precipitation and PET. It appears that the effects of PET on stream flow (reducing flow) exceeded the influence of P (increasing flow). Without considering the long-term change in air temperature, the contribution of LULC might have been underestimated in this study.

4 Discussion

4.1 Increased stream flow explained by the decreases in ET and LAI

The total stream flow (Fig. 12, Table 4), high flows, and low flows (Figs. 8, 9) in the QRB substantially increased during 2000–2013 while both LAI and ET decreased (Figs. 6, 12). Based on the watershed balance theory and comprehensive analyses using different methods, including FDC, CEM, and RRM, we attributed the dramatic increase in stream flow mainly to the changes in LULC and associated decrease in LAI, not climate (PET or P), for the following three complementary reasons.

First, LAI is a major controlling factor for ET, especially during the growing season (Sun et al., 2011a, b; Sun and Lockaby, 2012) and in humid, energy-limited southern China in particular (Liu et al., 2013). The strong relationship between MODIS ET and LAI (Figs. 6, 7) supported our hypothesis that urbanization dramatically reduced ET due to the reduction of LAI, thus the observed increase in stream flow is explained.

Second, regional annual ET is generally controlled by PET, P, and land surface conditions (Sun et al., 2005). A decrease in ET is normally caused by a decrease in P and/or PET (Sun et al., 2005; Sun et al., 2011a, 2011b). Our data suggested that the decrease in ET was not caused by PET or P because annual and growing-season PET significantly increased and overall precipitation did not change significantly. In fact, a negative correlation was found between ET and PET departures (Fig. 7). The DMC method that eliminated precipitation effects on stream flow suggested the QRB had a shift of annual stream flow upward around 2003 (Fig. 11). The two models for climate attribution analysis converged indicting that LULC contributed about 85 % of the observed variability in stream flow and precipitation contributed about 15 %. PET increased more dramatically during 2003–2013 than during 1986–2002 (Fig. 12). The increase in PET might have masked the decrease of ET due to the change in LULC, so we argue that the estimated 85 % contribution from LULC is a conservative estimate.

Third, the large decrease in LAI, as detected by remote sensing, corresponds closely to the dramatic conversion of rice paddy fields and an increase in total impervious area (TIA) during the urbanization campaign in the QRB since the early 2000s. Previous studies in the United States suggest that stream flow and water quality regimes are degraded when the TIA exceeds 10–20 % of the total watershed area (Arnold and Gibbons, 1996; Bledsoe and Watson, 2001). Our study result was consistent with the finding of the threshold response in literature, perhaps in the lower end of the spectrum (< 10 %). The detected decrease in LAI due to shrinking rice paddy areas has overwhelmed the impacts of climate change (i.e. rise of PET) on ET, highlighting the importance of LULC change in evaluating environmental change in the study region.

4.2 Regional hydrologic and environmental implications

Our findings complement findings from an earlier study of the same basin. Du et al. (2011, 2012) conducted a simulation study suggesting that the elevated high flow was mostly due to an increase in impervious surface area. Our new analysis suggested that in addition to the increase in impervious surface areas, other factors such as reduced ET could be the main causes that contributed to the observed increase in total flow and base flow in the study basin. The present study advanced the understanding of the processes of hydrologic disturbances. Study results had important hydrological and environmental implications for paddy field-dominated regions in China and elsewhere in East Asia.

First, we confirmed our hypothesis that converting water stress-free paddy fields to relatively ‘dry’ urban uses or impervious surfaces dramatically reduced ET (Fig. 1). Thus, converting wetlands, such as paddy fields, to impervious or built-up areas is expected to have a much higher magnitude of hydrologic impacts than for converting dry croplands or forests to urban land uses (Tsai, 2002; Boggs and Sun, 2011). The ET estimates based on two independent methods, watershed water balance and remote sensing, all showed large decreases in ET.

Second, the populated study region is prone to floods and droughts due to the nature of a strong summer monsoon climate (Gu et al., 2011). Urbanization is likely to exacerbate the flood risks during the monsoon season as a result of decreased ET, an increased impervious surface area, and decreased retention capacity (Kang et al., 1998; Kim et al., 2014). In addition, an increase in storm flow causes important concerns for stream channel stability, soil erosion, and reactivation of stream bed sediment and pollutants (Sun and Lockaby, 2012). This is of particular concern given the increasing trend of typhoon activities in southern China under climate change (Gu et al., 2011).

Third, the increasing trend in base flow found in this study is in somewhat contradiction to popular literature that suggests otherwise (Ott and Uhlenbrook, 2004; Kim et al., 2005; Price et al., 2011). We argue that the large reduction in ET from paddy fields might have overwhelmed the reduction of groundwater recharge from the increased impervious surfaces. The QRB is still dominated by croplands (62 % of land area in 2012) and the dramatic reduction in water loss from rice cultivation and irrigation needs likely elevated groundwater recharge from uplands or stream channels overall (Fig. 10). Other studies have shown that reductions in forest land coverage, thus reduction in ET, could increase base flow in the humid piedmont region in North Carolina (Boggs and Sun, 2011) and northeastern US (Lull and Sopper, 1969). Boggs and Sun (2011) conclude that the effects of vegetation removal on stream flow are most pronounced during the growing seasons when the contrast between ET from a vegetated surface and from an urbanized surface is the highest. Therefore, it is plausible that replacing paddy fields with high ET with urban land uses (e.g., lawns or impermeable surfaces) with low ET may result in similar effects as forest removal during urbanization. Future studies should examine the seasonality of the trend of base-flow change to confirm the effects of rice paddy conversion on base-flow and groundwater change.

4.3 Human factors affecting water balances

The landscape and stream networks of the QRB have been altered for thousands of years by humans. Our water balance analysis used a holistic approach to examine the natural rainfall–runoff relationships at the watershed scale with minimum attention to human water supply and use within the watershed. Currently, the QRB provides important ecosystem services such as drought/flood prevention, crop irrigation, recreation, tourism, and emergency drinking water supply to local communities. Patterns of groundwater withdrawal from local acquirers and inter-basin transfers are changing in the study basin as the speed of urbanization increases (Du et al., 2012; Zhou et al., 2014). To meet the increasing demand on water supply and flood controls by the urbanized communities, ponds, reservoirs, and drainage canals have been built. There are over 20 small reservoirs with the basin. These land-use patterns have undoubtedly further complicated the quantification of water balances for a large basin (Hao et al., 2015) since each land-use change factor might have affected different hydrologic components. Future studies should focus on process-based understanding of how land conversions affect ET processes and how this effect manifests at the watershed in affecting storm flow and base flow. In addition, inter-basin transfers must be addressed to reduce potential water balance errors by full accounting water supply and use within and across the QRB.

5 Conclusions

Using long-term hydrometeorological records, land-cover/land-use change information, and remote sensing-based biophysical and evapotranspiration data, this case study showed that stream-flow rates, both high flows and low flows, in the Qinhuai River basin increased from 1986 to 2013. A significant increase in stream flow and a decrease in ET were detected in the study basin and the changes were considered to be associated with urbanization, characterized by the shrinkage of rice paddy fields and an increase in impervious surface area. Urbanization that resulted in a reduction in LAI during the peak growing season overwhelmed the hydrological effects of climate warming and precipitation variability during the study period. The importance of rice paddy fields in regulating ET and hydrologic responses to disturbance has been underestimated in previous similar studies. There is a need in research to fully understand the ecohydrological processes that control the effects of land conversions on land surface energy and water balances at multiple scales. Models for assessing the ecosystem service function (e.g., climate cooling, flood retention) of rice paddy fields must include proper algorithms describing the hydrological processes including ET that links water and energy balances.

Rice cultivations have been practiced for thousands of years around the world. However, converting rice paddy fields to other uses in southern China and East Asia has been on the rise in a changing climate and changing demographics. Our study indicates that urbanization will likely increase the risk of flooding, heat islands, and social vulnerability due to the loss of ecosystem services of rice paddies. Minimizing and mitigating the hydrologic and environmental impacts of converting paddy fields downstream, while maintaining resource sustainability, requires an integrated watershed management approach that involves careful urban planning (Dunne and Leopold, 1978), landscape design (Dietz and Clausen, 2008), and irrigation management (Park et al., 2009).

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