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 streamflow 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 three decades. We found that streamflow increased by 58% and evapotranspiration (ET) decreased by 23% during 1986-2013 as a result of an increase in urban areas of three folds and reduction of rice paddy field by 27%. Both highflows and lowflows increased significantly by about 28% from 2002 to 2013. The increases in streamflow were consistent with the decreases in ET and leaf area index monitored by independent remote sensing MODIS data. Attribution analysis based on two empirical models indicted that land use/land cover change contributed about 82-108% of the observed increase in streamflow from 353±287 mm yr^{-1} during 1986-2002 to 556±145 during 2003-2013. We concluded that the reduction in ET was largely attributed to the cropland conversion 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 as one of the extreme types of contemporary hydrologic disturbances. The ongoing large-scale urbanization in the rice paddy-dominated regions in the humid southern China, and East Asia, will likely elevate stormflow volume, aggravate flood risks, and intensify urban heat island effects. Understanding the linkage 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) were also becoming increasingly important under a changing climate (Yang et al., 2015).

It is widely known that urbanization elevates peakflow 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 about changes in water balances and watershed hydrologic characteristics other than stormflow, such as total flow, lowflow, 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 the 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 peakflows 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 peakflow rate and storm volume (4-20%), but had very limited impacts 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 ‘homes of the 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 diched, 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 10 typical rice paddies in China concluded that their ecosystem service values exceed their economic values by three folds (Xiao et al., 2011). The rapid urbanization and population rise under 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 (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 to urbanization in paddy field-dominated landscapes (Du et al., 2011, 2012; Kim et al., 2014).

Converting paddies to urban land use have many cascading effects on the local environments (Figure 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 the humid southern China than in northern China or inland cities, indicating the stronger contrast of energy regime in the paddy-dominated regions than that 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 scenarios, 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 stormflow, ET reduction during urbanization is likely to cause large impacts on the local micro-climate, streamflow, and water quality on paddy field dominated watersheds (Figure 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) 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 (Figure 2), 2) test the hypothesis that urbanization in a paddy field dominated watershed dramatically reduced ET, thus altered water balances, and 3) explore the implications of urbanization for regional environmental change in southern China. In this study, we integrated long-term hydro-meteorological monitoring data and remote sensing-based ET and vegetation products. Multiple advanced detection techniques were used to examine trends of climate and streamflow 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 2,617 km^2. The QRB represents a typical landscape of the lower Yangtze River Delta region that is characterized as having a flat topography with natural river networks severely modified, and the land uses were dominated by paddy rice fields dotted with small irrigation ponds that were converted from natural wetlands over thousands of years (Figure 2). As the ‘Backyard Garden’ of Nanjing City, Capital of Jiangsu Province, the QRB is gradually 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 (Guo et al., 2012). The multi-year mean air temperature is 15.4°C. Mean air temperature (1961-2013) across the study basin has increased drastically at rate of 0.44 ^{o}C/decade from 1990 to 2013 (Figure 3), suggesting an increasing trend in evaporative potential during the past two decades. The mean (1986-2013) annual precipitation is 1,116 mm with 75% rainfall falling during April-October (Figure 4). The observed long-term mean annual streamflow (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% (1,188km^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 (Figure 2). Documents by Jiangsu Province Rural Statistics reported that rice planting area in the QRB shrank more than 25% from 995 km^2 in 2000 to 745 km^2 in 2010.

2.2 Land use, Climate, Streamflow, 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 thesis and journal papers for 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 (Figure 2). Streamflow 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 backflows from the Yangtze River (Figure 2). The daily streamflow data (2002-2003; 2006-2013) for the 'flooding periods' from May to October recorded at the Wuding Station were used to characterize highflows and lowflows. The total annual streamflow discharged to the Yangtze River was the sum of flows measured at the Wuding Station and the Inner Qinhuai Station. Total annual streamflow data for the period of 1986-2006 were reported in Du et al. (2011) and we collected daily and monthly streamflow data for other periods (Table 1).

Potential ET (PET) represents the maximum ecosystem evapotranspiration when soil water is not limited, such as 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 datasets provide consistent estimates of global actual ET at an eight-day and 1-km^2 resolution (Mu et al., 2011). Yuan et al. (2011) reprocessed the MODIS leaf areas index (LAI) datasets 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 were presented in Figure 4 along with other climatic variables to contrast seasonal ET, PET, and P that controlled seasonal streamflow.

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 α = 0.001, 0.01, 0.05, and 0.10, (2) The Sen's nonparametric method was 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 the residuals, which were referred 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 as 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 streamflow (Ma et al., 2010; Tang et al., 2011; Wei and Zhang, 2012). 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 streamflow frequency in daily and annual streamflow as a result of urbanization, respectively.

The trend of the baseflow component of the streamflow is one important indicator of change in soil water storage, i.e., soil moisture and groundwater conditions (Price et al., 2011). The Baseflow Index (BFI) program was used to separate the baseflow from measured total daily streamflow (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 (Figure 5), suggesting that BFI (baseflow/streamflow ratio) would not change much shorter than 7 days. We used a value of 0.9 for the turning point factor (*f*) to remove daily streamflow greater than100 m^3s^{-1}. Details of the methods to determine *N* and *f* can be found in Wahl and Wahl (1995).

2.4 Attribution Analysis

Once hydrologic change point was detected, we determined the individual contributions of climate and landcover/land use change to the observed streamflow change. We assumed that the observed streamflow 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}):

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

Then, the contribution of landcover/landuse ($\%\Delta Q$) can be estimated as:

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

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

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 deviation of Q (ΔQ_{0i}) and deviations P(ΔP_{0i}) and PET(ΔPET_{0i}) from the long-term means for the reference period:

$$\frac{\Delta Q_{0i}}{\bar{Q}_0} = \alpha \cdot \frac{\Delta P_{0i}}{\overline{P_0}} + \beta \cdot \frac{\Delta PET_{0i}}{\overline{PET_0}}$$

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 method while $\overline{Q_0}$ and $\overline{P_0}$ were mean measured annual streamflow and precipitation. $\overline{PET_0}$ represents mean annual potential ET estimated by the FAO reference ET method (Allen et al., 1994). Then, the effects of the climate change in the second period in question could be calculated as:

$$\Delta\bar{Q}_{clim} = \bar{Q}_{pre} - \bar{Q}_0$$

where $\Delta\overline{Q}_{clim}$, $\bar{Q}_{pre}$, $\bar{Q}_0$ represents the mean effects of climate change on annual streamflow during the second period, predicted mean streamflow using the climate (P and PET) for the second period and the empirical equation developed from the reference period, and observed streamflow 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 (${\sigma_{oi}}^2$) 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} is the annual Q and P for the reference period, respectively while ${\sigma_1}^2$ is the variance of the monthly P. The values of the three parameter, *a*, *b*, and *c* were derived using data from the reference period. The empirical model was then applied to estimate annual streamflow using precipitation for the second period (Q_{pre}) and finally to calculate the mean changes in Q ($\Delta\overline{Q}_{clim}$) as the differences between $\bar{Q}_{pre}$ and mean streamflow for the reference period ($\bar{Q}_0$).

3 Results

3.1 Land conversion and change in LAI

During 2000-2012, the QRB has gone 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) (see insert in Figure 2). The land cover change matrix showed 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 small from 2000 to 2012 (insert Figure 2 and Table 2), 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 = -2.08 and Z statistic = -2.41, respectively (Table 3) (Figure 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) (Figure 4). The ET linear trend during the peak growing season (July-August) accounted for 32% of the total annual trend. Overall, ET showed a similar decreasing trend with LAI in the peak growing season during 2000-2013 (Figure 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 (Figure 7).

3.3 Changes in streamflow characteristics

The FDC analysis for the flow measured at Wuding Sluice Gate indicated that both daily highflows and lowflows were elevated during 2009-2013 compared to 2002-2008, with the median flow rates increased from $30m^3s^{-1}$ to $38m^3s^{-1}$ (Figure 8). The extreme high flow in 2002-2008 was caused by one extreme rainfall event in July, 2007 (rainfall = 339 mm) that resulted in widespread flooding. The baseflow analysis also showed a significant (p = 0) increasing trend during 2006-2013 (Figure 9). The increase in baseflow or low flow coincided with the observations that the groundwater levels in the study basin were on the rise in recent decade as a result of groundwater management and likely landuse change in the recent decade (Figure 10). The runoff coefficient (Streamflow/Precipitation ratio) during May-October period (wet, flooding seasons) increased significantly from 0.32 to 0.41, or 28%, during 2002-2013 (Z statistic = 2.89, $p < 0.01$) (See insert in Figure 8).

3.4 Changes in Annual Watershed Water Balances

The DMC analysis identified a clear ‘break point’ of total annual streamflow (Q) around 2003

(Figure 11). The slopes of the regression lines between accumulated precipitation and streamflow increased from 0.27 to 0.50. Mean annual streamflow significantly increased from 353 mm to 556 mm from period 1 (1986-2002) to period 2 (2003-2013) (Figure 12). This represented an increase of runoff coefficient (Q/P) from 0.32 to 0.49, a 53% increase. The trend of annual streamflow was influenced heavily by 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 ET/P ratio by 25%.

3.5. Contributions of LULC change and climate change and variability

The two models gave consistent results on the contributions of climate change ($\%\Delta Q_{clim}$) and LULC change ($\%\Delta Q_{lulc}$) to the observed annual increase (203 mm) in streamflow 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 streamflow 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 streamflow 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 streamflow (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 streamflow explained by the decreases in ET and LAI

The total streamflow (Figure 12, Table 4), highflows, and lowflows (Figures 8, 9) in the QRB have substantially increased during 2000-2013 while both LAI and ET have decreased (Figure 6, Figure 12). Based on the watershed balance theory and comprehensive analyses using different method including FDC, CEM, RRM, we attributed the dramatic increase in streamflow 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, 2011b; 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 (Figures 6, Figure 7) supported our hypothesis that urbanization dramatically reduced ET due to the reduction of LAI, thus explained the observed increase in streamflow.

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 (Figure 7). The DMC method that eliminated precipitation effects on streamflow suggested the QRB had a shift of annual streamflow upward around 2003 (Figure 11). The two models for climate attribution analysis converged indicting that LULC contributed about 85% of the observed variability in streamflow and precipitation contributed about 15%. PET increased more dramatically during 2003-2013 than during 1986-2002 (Figure 12). The increase in PET might have masked the decrease of ET due to 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 corresponded closely to the dramatic conversion of rice paddy fields and 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 total watershed area (Arnold and Gibbons, 1996; Bledsoe and Watson, 2001). Our study result was consistent with the finding of the threshold response in the 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 for the same basin. Du et al. (2011, 2012) conducted a simulation study suggesting that the elevated highflow were 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 baseflow 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 (Figure 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 that for converting dry croplands or forests to urban land uses (Tsai's, 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 stormflow has important concerns on stream channel stability, soil erosion, and reactivation of streambed sediment and pollutants (Sun and Locakby, 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 baseflow found in this study is in somewhat contradiction to the 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 (Figure 10). Other studies have shown that reductions in forest land coverage, thus reduction in ET, could increase baseflow in the humid piedmont region in North Carolina

(Boggs and Sun, 2011) and northeastern U.S. (Lull and Sopper, 1969). Boggs and Sun (2011) conclude that the effects of vegetation removal on streamflow 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 effect as forest removal during urbanization. Future studies should examine the seasonality of the trend of baseflow change to confirm the effects of rice paddy conversion on baseflow 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 the 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 in the study region (Du et al., 2012; Zhou et al., 2015). 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 landuse patterns further undoubtedly have complicated the quantification of water balances for a large basin (Hao et al., 2015) since each landuse change factor might have affected different hydrologic components. Future studies should focus on process-based understanding how land conversions affect the ET processes and this effect manifests at the watershed in affecting stormflow and baseflow. 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 streamflow rates, both highflows and lowflows, in the Qinhuai River Basin have increased from 1986 to 2013. A significant increase in streamflow and a decrease in ET in the study basin were detected, and the changes were considered to be associated with urbanization characterized as 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 research need 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 under a changing climate and 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. To minimize and mitigate the hydrologic and environmental impacts of converting paddy fields down streams 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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Table 1. A summary of landuse, 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 thesis and journal papers (Du et al., 2012; Chen, Du, 2014; Gong et al., 2013)	Land use / Land cover types	1988,1994, 2000, 2004, 2007 and 2012	30 m
Climate	Jiangsu meteorological bureau (4 meteorological stations)	Precipitation, radiation, temperature, wind speed, and humidity	1961-2013	Daily,
Streamflow	Two hydrological stations: the Wuding Sluice Gate and the Inner Qinhuai Sluice Gate. Published journal papers (Du et al., 2011)	Streamflow	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 datasets (Mu et al., 2011)	Actual ET	2000-2013	Eight-day and 1-km^2 resolution
Leaf Area Index (LAI)	Improved MODIS LAI datasets(http://globalchange bnu.edu.cn/research/lai) (Yuan et al.,2011)	LAI	2000-2013	Eight-day and 1-km^2 resolution

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	∑ (2000)
Dry crop lands	320	226	7	8	175	736
Paddy fields	257	681	6	24	220	1,188
Forest	74	2	264	2	24	366
Water	16	12	2	59	14	104
Urban built-up areas	26	13	3	3	178	223
∑ (2012)	693	933	283	96	611	2,617
Area change from 2000 to 2012	-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.

Table 4. Modeled contributions of land use change and climate change on the increase in streamflow (mm yr^{-1}) by the Climate Elasticity Model (CEM) and Rainfall Runoff Model (RRM).

Period	$\overline{P}$	$\overline{PET}$	$\overline{Q}$	ΔQ_o	CEM (α=0.27; β=-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(-8%)	218±131(108%)	36 ± 169(18%)	167 ± 100(82%)

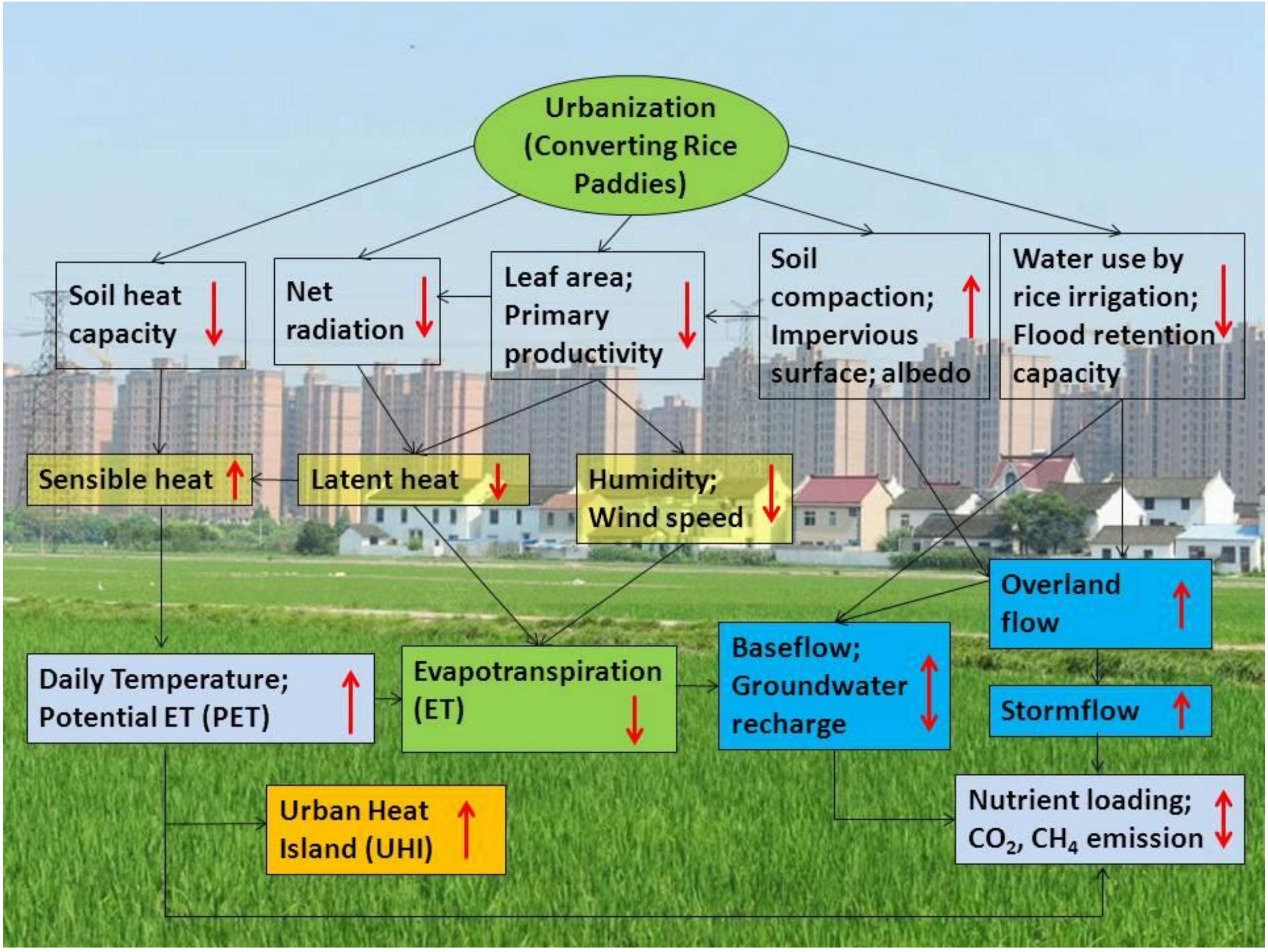

Fig. 1. A conceptual model illustrating the potential hydrologic and environmental impacts of converting rice paddies to urban uses in the Yangtze River Delta region. Arrows represent directions (up or down or both) of change (Background photo credit: http://blog.sciencenet.cn/blog-578415-712508.html).

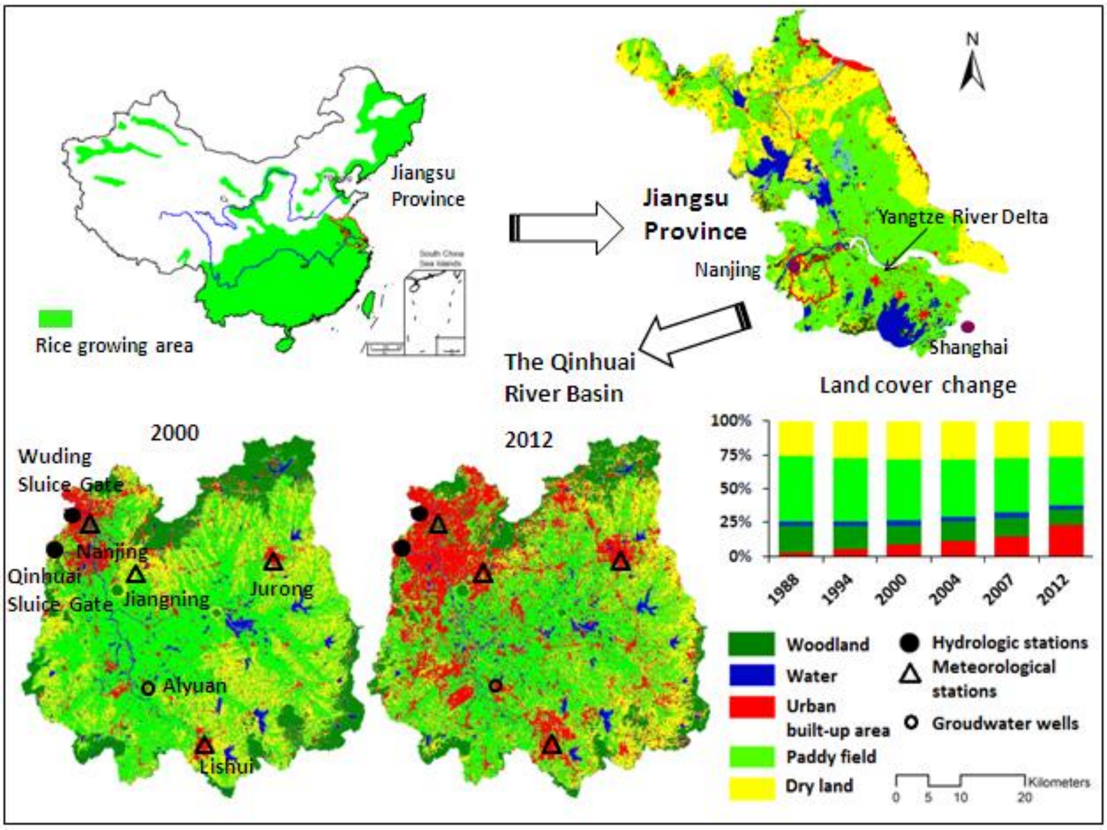

Fig. 2. Watershed location, instrumentation, and land use change patterns in the Qinhuai River Basin, Yangtze River Delta in southern China. The insert map showing changes in land use derived from published data (Du et al., 2012; Chen and Du, 2014) (1988 and 1994) and Landsat 7 ETM+ images (2000-2012).

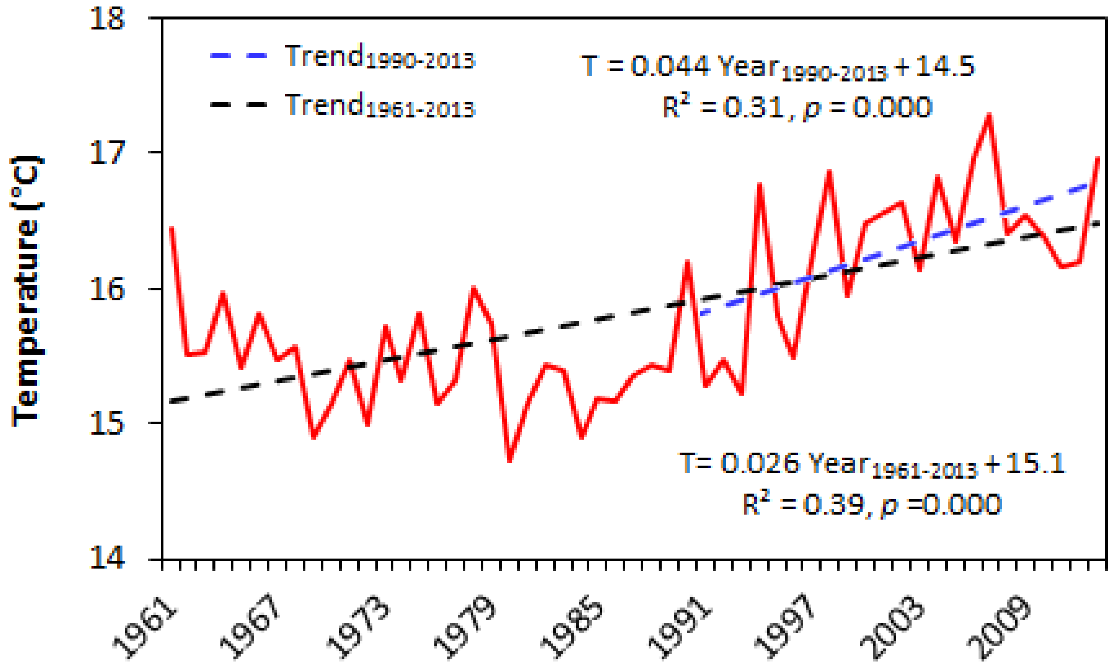

Fig. 3. Mean annual air temperature change across four meteorological stations in the Qinhuai River Basin in southern China during 1961-2013.

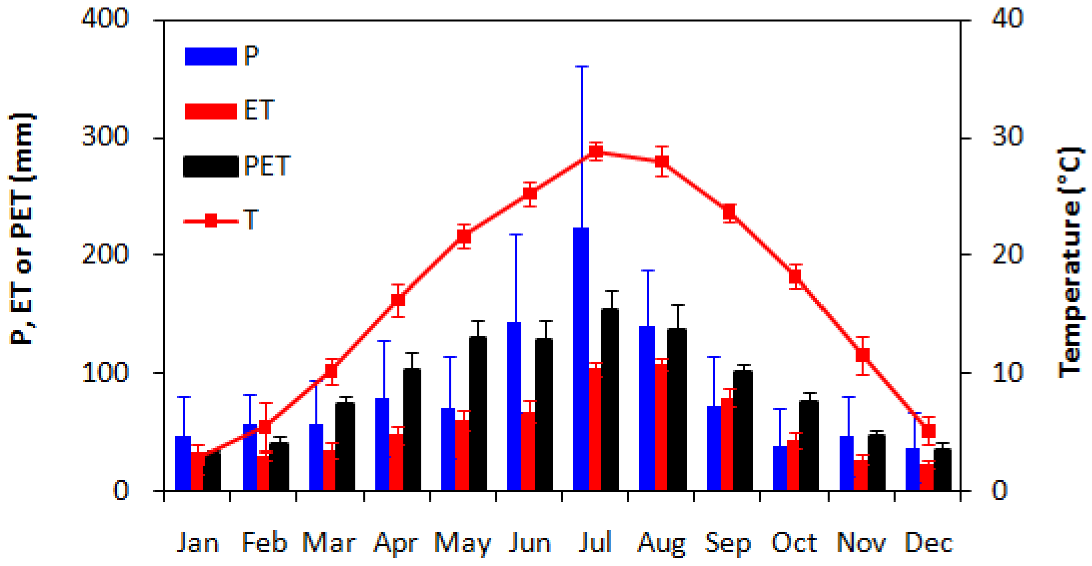

Fig. 4. Mean monthly precipitation (P) (1986-2013), MODIS evapotransiration (ET) (2000-2013), potential evapotranspiration (PET) (2000-2013) and temperature (T) (1986-2013), and the vertical lines are standard deviation.

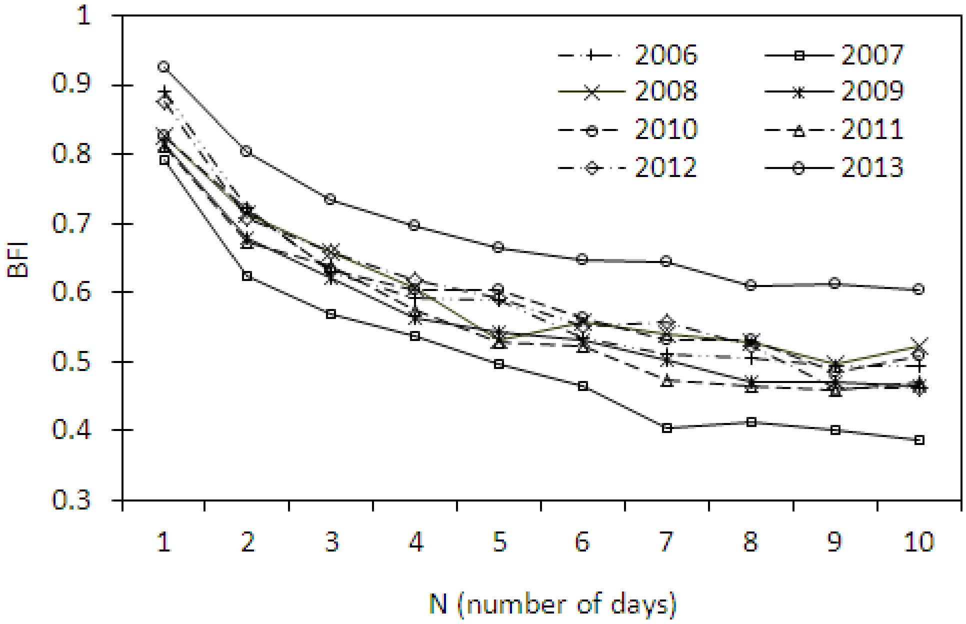

Fig. 5. Sensitivity of Base-flow Index (BFI) to the number of days (*N*) used to select the minimum value in baseflow separation analysis from 2006 to 2013 at the Wuding Station located at the outlet of the Qinhuai River Basin.

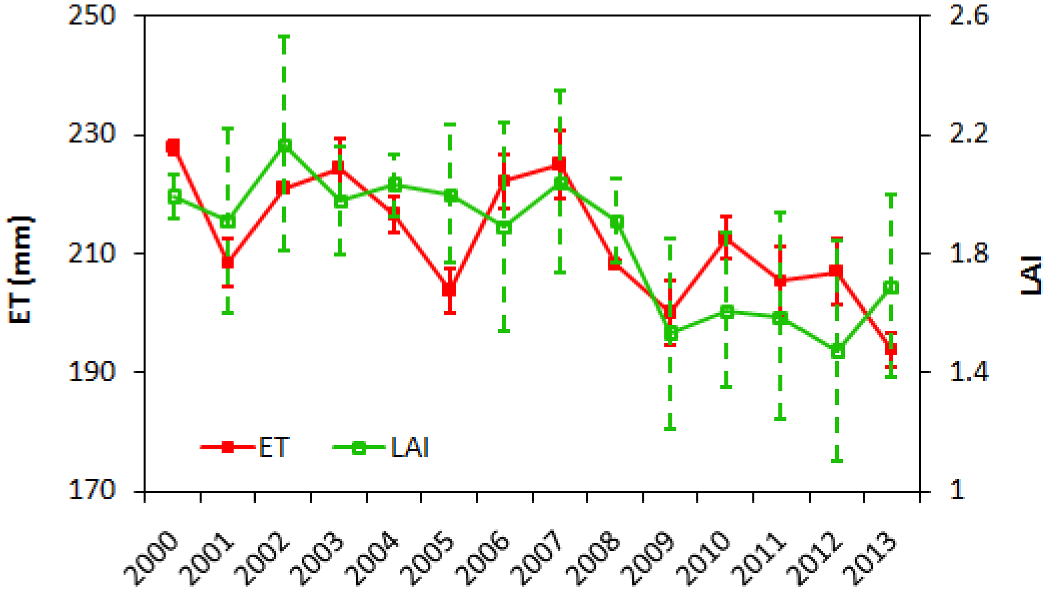

Fig. 6. Total MODIS ET (mm per two months) and mean LAI during the peak growing season (July - August) over 2000-2013 in the Qinhuai River Basin. Vertical lines represent standard deviation across space.

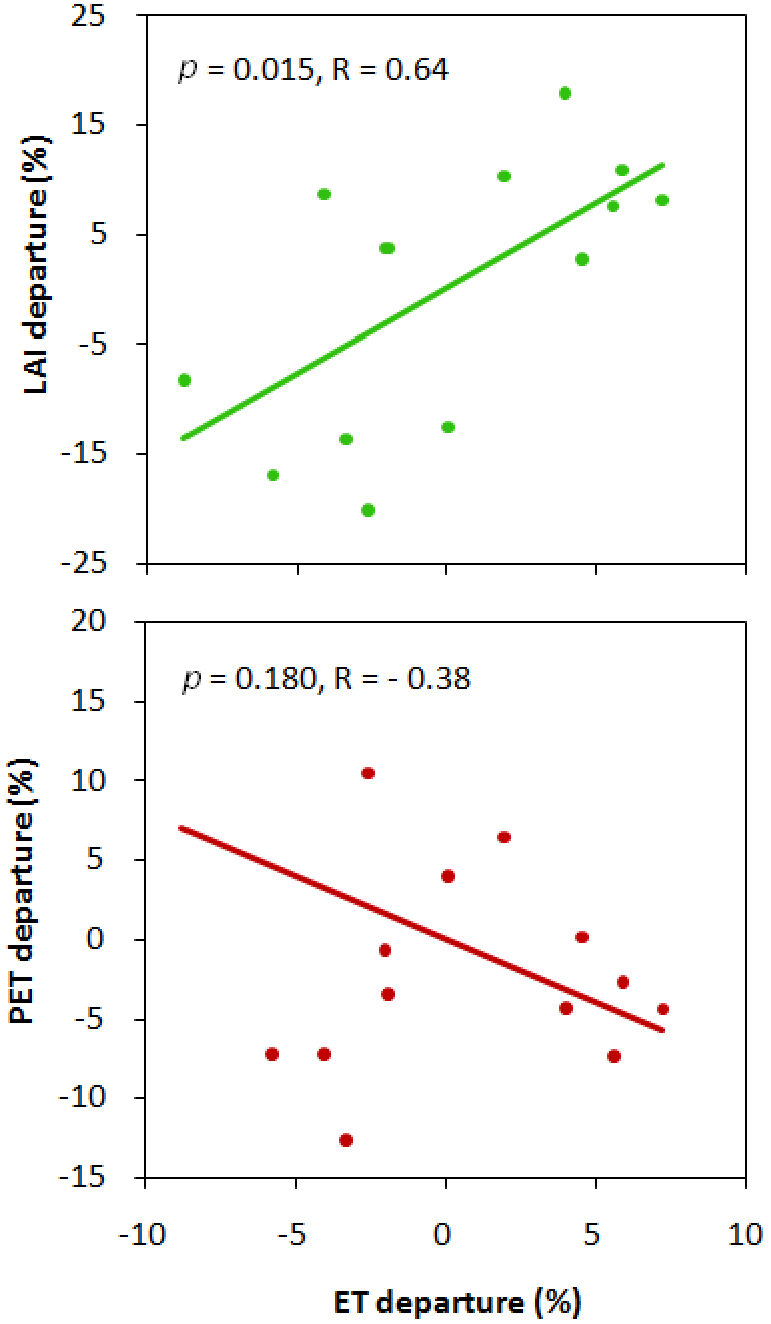

Fig. 7. Correlations of the departures of basin-level ET with (a) the departures of mean leaf area index (LAI) and (b) the departures of PET in the peak growing season (July-August) over 2000-2013 in the Qinhuai River Basin.

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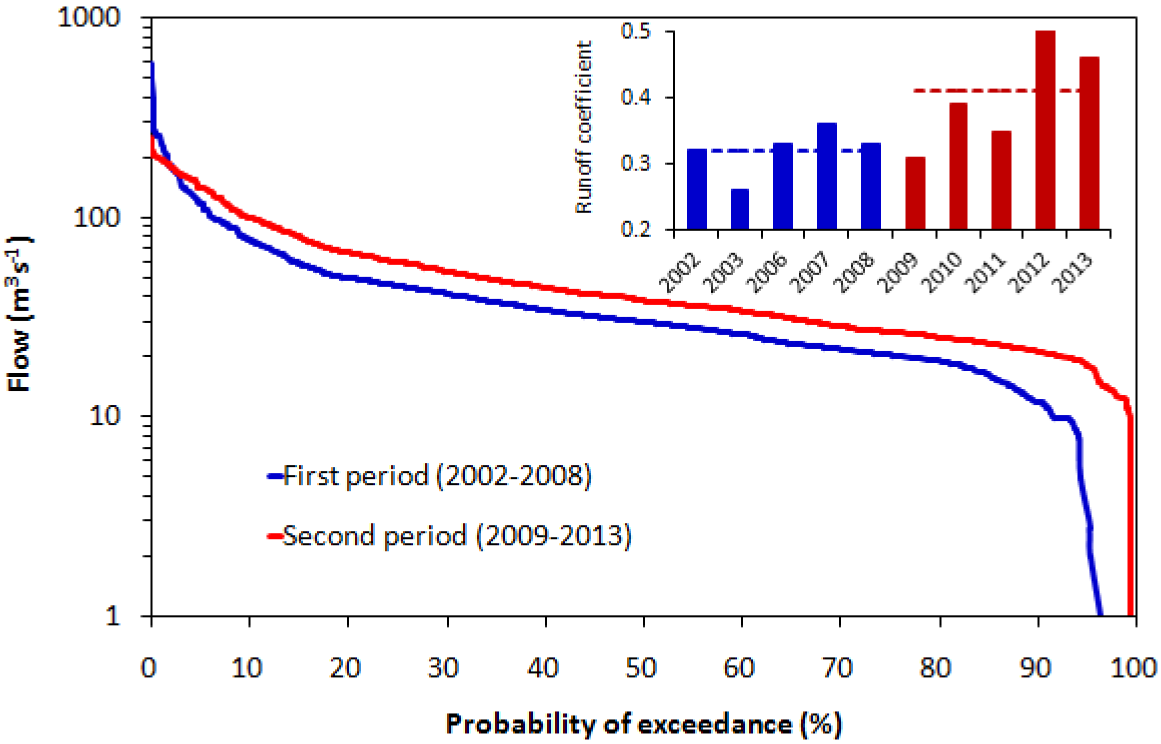
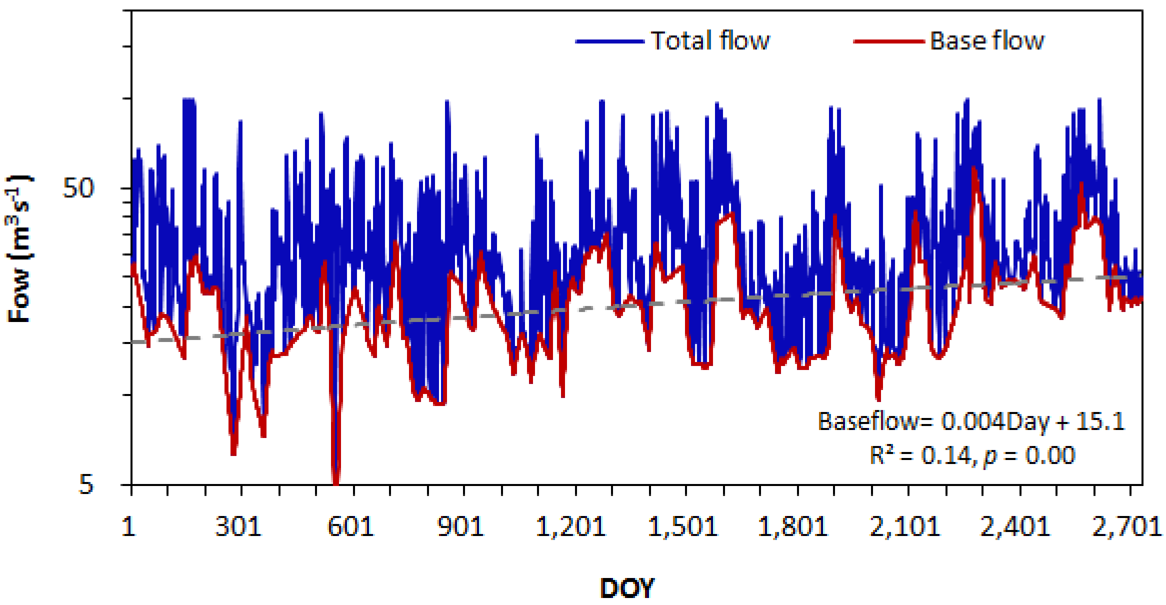


Fig. 8. Flow duration curves for mean daily flow in the first period (2002-2003 and 2006-2008) and the second period (2009-2013) (May-October) measured at the Wuding Station in the Qinhuai River Basin. Insert is runoff coefficient, the ratio of streamflow/precipitation for the period from May to October when the flow control gate was open.



659

660 **Fig. 9.** Trend of daily base flow separated from total stream flow measured at the Wuding Station

661 during 2006-2013. DOY is the number of accumulated days since January 1, 2006.

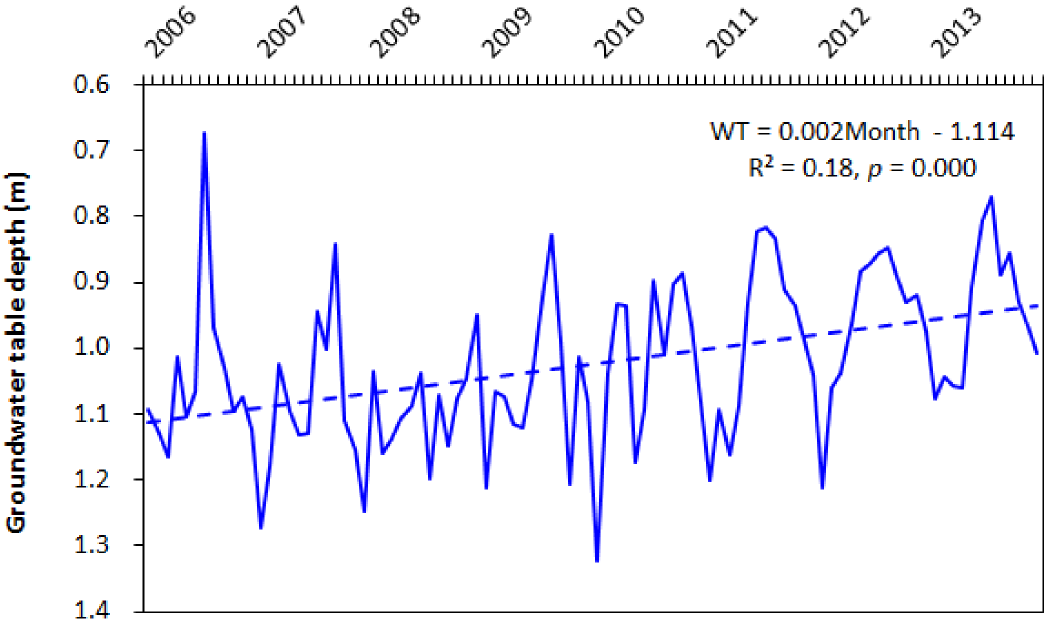


Fig. 10. The trend of monthly groundwater table depth fluctuations measured at the Aiyuan Well Station in the Lishui sub basin during 2006-2013.

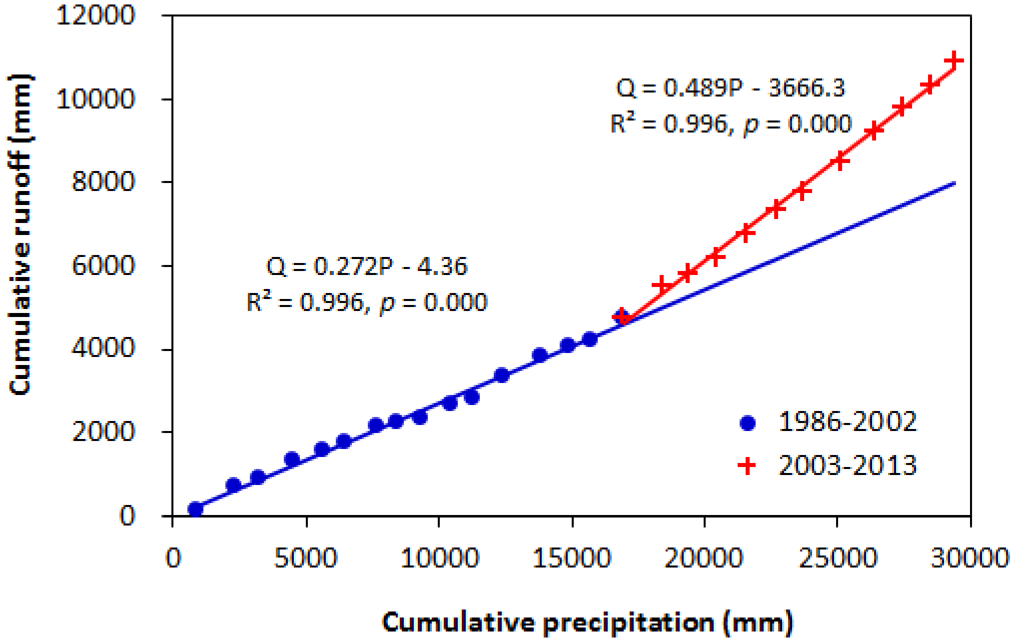


Fig. 11. Double mass curves showing the relationships between accumulated annual precipitation (P) and total streamflow (Q) for the Qinhuai River Basin (1986-2013). The extreme wet year of 1991 was removed from the analysis.

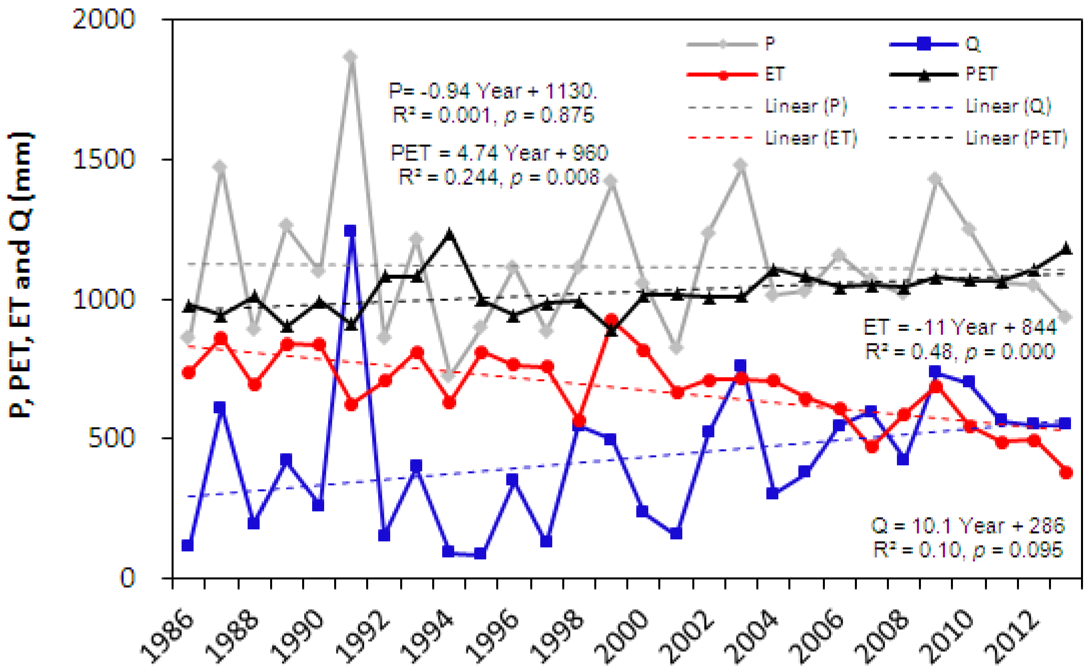


Fig. 12. Trend of annual water balance and potential evapotranspiration (PET) for the Qinhuai River Basin from 1986-2013. ET was estimated as the difference between precipitation (P) and measured streamflow (Q).