Hydrol. Earth Syst. Sci. Discuss., 12, 1941–1972, 2015
www.hydrol-earth-syst-sci-discuss.net/12/1941/2015/
doi:10.5194/hessd-12-1941-2015

Hydrology and Earth System Sciences
Discussions
Open Access

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

L. Hao[1], G. Sun[2], Y. Liu[3], J. Wan[4], M. Qin[1], H. Qian[1], C. Liu[5], R. John[6], P. Fan[7], and J. Chen[6]

[1]International Center for Ecology, Meteorology, and Environment (IceMe), Jiangsu Key Laboratory of Agricultural Meteorology, Nanjing University of Information Science and Technology (NUIST), Nanjing 210044, China
[2]Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, NC 27606, USA
[3]Center for Forest Disturbance Science, Southern Research Station, USDA Forest Service, Athens, GA 30602, USA
[4]China Institute of Water Resources and Hydropower Research, Beijing 100048, China
[5]State Key Laboratory for Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China
[6]Center for Global Change and Earth Observations (CGCEO), and Department of Geography, Michigan State University, East Lansing, MI 48823, USA
[7]School of Planning, Design, and Construction (SPDC) and Center for Global Change and Earth Observations (CGCEO), Michigan State University, East Lansing, MI 48823, USA

Received: 14 January 2015 – Accepted: 1 February 2015 – Published: 13 February 2015

Correspondence to: G. Sun (gesun@ncsu.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

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 declining 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 in the region 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. The reduction in ET and increase in streamflow was attributed to the large cropland conversion that overwhelmed the effects of regional climate warming and climate variability. Converting traditional rice paddy fields to urban use dramatically altered land surface conditions from a water-dominated to a human-dominated landscape, 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 change and changes in hydrological processes is essential for better management of urbanizing watersheds.

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

HESSD
12, 1941–1972, 2015

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). 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 stormflows, such as total flows, lowflows, 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

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

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). 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 (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). 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 (Fig. 1).

The overall goal of this study was 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

HESSD
12, 1941–1972, 2015

affected the water balances and hydrologic characteristics of the Qinhuai River Basin (QRB), a typical landscape of the YRD (Fig. 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 vegetation leaf area index and land use dynamics.

2 Methods

2.1 The Qinhuai River Basin (QRB)

As one of the key 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 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 (Fig. 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 across the study basin has increased drastically at rate of 0.44 °C $decade^{-1}$ since 1990s (Fig. 3). The mean annual precipitation is 1050 mm with 75 % rainfall falling during April–October (Fig. 4). The observed long-term mean annual streamflow is about 430 mm, concentrated from June to August. The QRB has seen rapid urbanization during the past decade. The impervious surface area increased from 3 to 8 % from 1988 to 2003, but jumped to 25 % in 2012, and the area of rice paddy fields decreased from 45 % of the total land area in 2001 to 37 % in 2012 (Du et al., 2011, 2012; Chen and Du, 2014) (Fig. 2). Jiangsu Province Rural Statistics also 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 compiled land use and land cover data acquired for the period from 1988 to 2012 from multiple sources, including published thesis and journal papers for the study basin (Du et al., 2012; Chen and Du, 2014), and publically release land use databases for China such as the 30 m Landsat data for 2000 created by the Chinese Academy of Sciences (Liu et al., 2009), and for 2010 we 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). 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 (Fig. 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.

Potential ET (PET) represents the maximum ecosystem evapotranspiration when soil water is not limited, such as the case of paddy fields. PET represents a compre-

HESSD
12, 1941–1972, 2015

hensive 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. Monthly PET and MODIS ET rates were presented in Fig. 4 along with other climatic variables to contrast seasonal ET, PET, and P that are control seasonal streamflow.

2.3 Change detection

Three statistical methods were used to analyze the temporal changes in the hydroclimatic 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) the non-parametric Sen's method for estimating the slope of an existing trend (Gilbert, 1987), and (3) Dynamic Harmonic Regression (DHR) method for determining the change rates for meteorological, hydrological, and LAI time series based on the Captain Toolbox (Taylor et al., 2007). 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, distribution, and timing of changes in annual streamflow as a result of urbanization. The Baseflow Index (BFI) program was used to separate the baseflow and stormflow from measured daily streamflow (Wahl and Wahl, 1995). These hydrologic detection methods have been widely used for understanding the effects of land use change and climate change on streamflow (Ma et al., 2010; Tang et al., 2011; Wei and Zhang, 2012).

HESSD
12, 1941–1972, 2015
Urbanization dramatically altered the water balances
L. Hao et al.

3 Results

3.1 Land conversion and change in LAI

During 1988–2012, the QRB has gone through dramatic land cover changes characterized by an increase in impervious areas and a decrease in paddy fields (Du et al., 2011, 2012; Chen and Du, 2014) (see insert in Fig. 2). The land cover change matrix showed that, from 2000 to 2010, the area of urban lands increased 482 km^2 or 307 % at the expense of cropland (−408 km^2, or −19 %) and forest lands (−133 km^2, or −50 %) (Table 2). Since dryland changed relatively small from 1988 to 2010 (insert Fig. 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 1) (Fig. 5). Since the major decrease in land use was paddy rice (Du et al., 2011), we believe that 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 1). 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 1). In contrast, the mean temperature had a significant increase during the long period of 1961–2013 (Z statistic = 2.21, $p < 0.05$) (Fig. 3). Both annual and growing season PET rose significantly by 7.52 mm yr^{-1} (Z statistic = 2.52, $p < 0.05$) and 5.06 mm yr^{-1} (Z statistic = 2.41, $p < 0.05$), respectively, an opposite trend of the actual ET (Table 1). The DHR method also identified a rising trend for annual PET.

HESSD
12, 1941–1972, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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 (−1.69 mm yr^{-1}, Z statistic = 2.30, $p < 0.05$) (Table 1) (Fig. 4). The ET change during the peak growing season (July–August) accounted for 32 % of the total annual change. Overall, ET showed a similar decreasing trend with LAI in the peak growing season during 2000–2013 (Fig. 5). 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 ($R = -0.38$, $p = 0.18$) (Fig. 6).

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 30 to 38 m^3 s^{-1} (Fig. 7). 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 (Fig. 8). Our results showed that N, the number of days over which a minimum flow could be determined was 7 for the QRB. We used a value of 0.9 for the turning point factor, f, to remove daily streamflow greater than 100 m^3 s^{-1}. Details to determine N and f can be found in Wahl and Wahl (1995). The increase in baseflow or low flow coincided with the reported observations that the groundwater levels in the study basin were on the rise in recent decade as a result of groundwater management (data not shown). 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 Fig. 7).

HESSD
12, 1941–1972, 2015

3.4 Changes in annual watershed water balances

The DMC analysis identified a clear "break point" of total annual streamflow (Q) around 2003 (Fig. 9). The slopes of the regression lines between accumulated precipitation and streamflow increased from 0.26 to 0.50. Mean annual streamflow significantly increased from 353 to 556 mm from period 1 (1986–2002) to period 2 (2003–2013) (Fig. 10). 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 to 578 mm from period 1 to period 2, representing a decline in ET by 23 % or ET/P ratio by 25 %.

4 Discussion

4.1 Increased streamflow explained by the decreases in ET and LAI

The total streamflow (Fig. 10), and highflows and lowflows (Figs. 7 and 8) in the QRB have substantially increased during 2000–2013 while both LAI and ET have decreased (Figs. 5 and 10). Based on the watershed balance theory and all evidence of FDC analysis, we attributed the dramatic increase in streamflow to the 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. 5) 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 an increase in P and PET. Our data suggested that the decrease in ET was not caused by PET or P because annual and growing season PET significantly increased and precipitation did not change significantly. In fact, a negative correlation was found between ET and PET departures (Fig. 5). The DMC method that eliminated precipitation effects on streamflow also suggested the QRB had a shift of annual streamflow upward around 2003.

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 land use change in evaluating environmental change in the study region.

4.2 Regional hydrologic and environmental implications

Our findings complement an earlier study for the same basin that concluded that the elevated highflows were due to an increase in impervious surface area (Du et al., 2011, 2012). 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 lowflows in the study basin. The present study advanced the understanding of the processes of hydrologic disturbances and has important 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).

HESSD
12, 1941–1972, 2015

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. The ET estimates based on two independent methods, watershed water balance and remote sensing, all show large deceases 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 of rice paddy fields (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 was in contradiction to the popular literature that suggested otherwise (Ott and Uhlenbrook, 2004; Kim et al., 2005; Price et al., 2011). 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 (65 % of land area in 2010) and the dramatic reduction in water loss from rice cultivation and irrigation needs likely elevated groundwater recharge from uplands or stream channels overall. Reductions in forest land coverage, thus reduction in ET, have showed to increase baseflow in the humid piedmont region in North Carolina (Boggs and Sun, 2011) and northeastern US Lull and Sopper (1969). Boggs and Sun (2011) argue that the effects of vegetation removal on streamflow are most pronounced during the growing seasons when the contrast of ET between a vegetated surface and an urbanized surface is the greatest. Therefore, it is plausible that replacing paddy fields with high ET with urban land uses (grass or impermeable surface) with low ET may result in similar effect as forest removal during

HESSD
12, 1941–1972, 2015

urbanization. Future studies should examine the seasonality of the trend of baseflow change to confirm the effects of rice paddy on baseflow.

Fourth, according to the regional energy balance theory, a strong reduction in ET or latent heat from urbanization likely results in an increase in sensible heat (Dow and DeWalle, 2000), a major energy source of “urban heat islands” (UHI) effects. The QRB is known to be one of the “Four Ovens” in China for its hot summer weather and the QRB has seen a warming trend during the past three decades (Fig. 3). Although it is beyond the scope of this study to link the observed rising air temperature and urban UHI to land use change in the study region, our study suggests that a reduction in ET from paddy fields is likely to further aggravate the UHI effects under a humid climate (Zhao et al., 2014). Our study is consistent with the notion by local people that paddy fields behave as large “air conditioners”. An earlier study indeed rated the YRD as the most impacted region from urbanization across China in terms of UHI impacts (He et al., 2007). A study by Zhou et al. (2014) on UHI among China’s 32 cities concluded that UHI effects dropped more sharply in the humid southern China than in northern China or inland cities. Our study offered new evidence to explain the causes of the regional urban heat island effects from the point of view of hydrological changes.

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. The changes in water balances were mainly through the reduction in growing season ET and not by increasing impervious surfaces alone. 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

HESSD
12, 1941–1972, 2015

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 practices 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).

Acknowledgements. This study was supported by the Natural Science Foundation of China (71373130), the Jiangsu Key Laboratory of Agricultural Meteorology Fund (No. KYQ1201), the National Key Basic Research Program of China (2013CB430200, 2013CB430206), and IceMe of NUIST. Partial support was from the Southern Research Station, USDA Forest Service.

References

Allen, R. G., Smith, M., Perrier, A., and Pereira, L. S.: An update for the definition of reference evapotranspiration, ICID Bull., 43, 1–34, 1994.

Arnold, C. L. and Gibbons, C. J.: Impervious surface coverage: the emergence of a key environmental indicator, J. Am. Plann. Assoc., 62, 243–258, 1996.

Barron, O. V., Barr, A. D., and Donn, M. J.: Effect of urbanisation on the water balance of a catchment with shallow groundwater, J. Hydrol., 485, 162–176, doi:10.1016/j.jhydrol.2012.04.027, 2013.

Bledsoe, B. P. and Watson, C. C.: Effects of urbanization on channel instability, J. Am. Water Resour. As., 37, 255–270, doi:10.1111/j.1752-1688.2001.tb00966.x, 2001.

Boggs, J. L. and Sun, G.: Urbanization alters watershed hydrology in the Piedmont of North Carolina, Ecohydrology, 4, 256–264, doi:10.1002/Eco.198, 2011.

Brath, A., Montanari, A., and Moretti, G.: Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty), J. Hydrol., 324, 141–153, doi:10.1016/j.jhydrol.2005.10.001, 2006.

Caldwell, P. V., Sun, G., McNulty, S. G., Cohen, E. C., and Moore Myers, J. A.: Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US, Hydrol. Earth Syst. Sci., 16, 2839–2857, doi:10.5194/hess-16-2839-2012, 2012.

Chen, A. L. and Du, J. K.: Simulation and forecast of land cover pattern in Qinhuai River Basin based on the CA-Markov model, Remote Sens. Land Resour., 26, 184–189, doi:10.6046/gtzyyg.2014.02.29, 2014.

Dietz, M. E. and Clausen, J. C.: Stormwater runoff and export changes with development in a traditional and low impact subdivision, J. Environ. Manage., 87, 560–566, doi:10.1016/j.jenvman.2007.03.026, 2008.

Dow, C. L. and DeWalle, D. R.: Trends in evaporation and Bowen ratio on urbanizing watersheds in eastern United States, Water Resour. Res., 36, 1835–1843, doi:10.1029/2000wr900062, 2000.

Du, J. K., Li, C., Rui, H., Li, Q., Zheng, D., Xu, Y., and Hu, S.: The change detection of impervious surface and its impact on runoff in the Qinhuai River Basin, China, in: 19th International Conference on Geoinformatics, Shanhai, China, 24–26 June 2011, 1–5, 2011.

Du, J. K., Qian, L., Rui, H. Y., Zuo, T. H., Zheng, D. P., Xu, Y. P., and Xu, C. Y.: Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China, J. Hydrol., 464, 127–139, doi:10.1016/j.jhydrol.2012.06.057, 2012.

Dunne, T. and Leopold, L.: Water in Environmental Planning, W H Freeman and Company Press, New York, 1978.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., and Snyder, P. K.: Global consequences of land use, Science, 309, 570–574, doi:10.1126/science.1111772, 2005.

Gilbert, R. O.: Statistical Methods for Environmental Pollution Monitoring, VanNostrand Reinhold Press, New York, 1987.

Gong, P., Wang, J., Yu, L., Zhao, Y. C., Zhao, Y. Y., Liang, L., Niu, Z. G., Huang, X. M., Fu, H. H., Liu, S., Li, C. C., Li, X. Y., Fu, W., Liu, C. X., Xu, Y., Wang, X. Y., Cheng, Q., Hu, L. Y.,

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

Yao, W. B., Zhang, H., Zhu, P., Zhao, Z. Y., Zhang, H. Y., Zheng, Y. M., Ji, L. Y., Zhang, Y. W., Chen, H., Yan, A., Guo, J. H., Yu, L., Wang, L., Liu, X. J., Shi, T. T., Zhu, M. H., Chen, Y. L., Yang, G. W., Tang, P., Xu, B., Ciri, C., Clinton, N., Zhu, Z. L., Chen, J., and Chen, J.: Finer resolution observation and monitoring of global land cover: first mapping results with Landsat TM and ETM+ data, Int. J. Remote Sens., 34, 2607–2654, 2013.

Gu, C., Hu, L., Zhang, X., Wang, X., and Guo, J.: Climate change and urbanization in the Yangtze River Delta, Habitat Int., 35, 544–552, 2011.

He, B., Wang, Y., Takase, K., Mouri, G., and Razafindrabe, B. H. N.: Estimating land use impacts on regional scale urban water balance and groundwater recharge, Water Resour. Manag., 23, 1863–1873, doi:10.1007/s11269-008-9357-2, 2009.

He, J. F., Liu, J. Y., Zhuang, D. F., Zhang, W., and Liu, M. L.: Assessing the effect of land use/land cover change on the change of urban heat island intensity, Theor. Appl. Climatol., 90, 217–226, doi:10.1007/s00704-006-0273-1, 2007.

Jacobson, C. R.: Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review, J. Environ. Manage., 92, 1438–1448, 2011.

Jonsson, P. and Eklundh, L.: TIMESAT – a program for analyzing time-series of satellite sensor data, Comput. Geosci.-UK, 30, 833–845, 2004.

Kang, I. S., Park, J. I., and Singh, V. P.: Effect of urbanization on runoff characteristics of the On-Cheon stream watershed in Pusan, Korea, Hydrol. Process., 12, 351–363, 1998.

Kendall, M. G.: Rank Correlation Methods, Charles Griffin Press, London, 1975.

Kim, S. J., Kwon, H. J., Park, G. A., and Lee, M. S.: Assessment of land-use impact on streamflow via a grid-based modelling approach including paddy fields, Hydrol. Process., 19, 3801–3817, doi:10.1002/Hyp.5982, 2005.

Kim, Y. J., Kim, H. D., and Jeon, J. H.: Characteristics of water budget components in paddy rice field under the Asian monsoon climate: application of HSPF-paddy model, Water-Sui., 6, 2041–2055, doi:10.3390/W6072041, 2014.

Liu, J., Tian, H., Liu, M., Zhuang, D., Melillo, J. M., and Z. Zhang, Z.: China's changing landscape during the 1990s: large-scale land transformations estimated with satellite data, Geophys. Res. Lett., 32, L02405, doi:10.1029/2004GL021649, 2005.

Liu, Y., Zhou, Y., Ju, W., Chen, J., Wang, S., He, H., Wang, H., Guan, D., Zhao, F., Li, Y., and Hao, Y.: Evapotranspiration and water yield over China's landmass from 2000 to 2010, Hydrol. Earth Syst. Sci., 17, 4957–4980, doi:10.5194/hess-17-4957-2013, 2013.

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

Lull, H. W. and Sopper, W. E.: Hydrologic effects from urbanization of forested watersheds in the Northeast USA, Forest Service Research Paper NE-146, Northeastern Forest Experiment Station, Upper Darby, PA, USA 1969.

Ma, H. A., Yang, D. W., Tan, S. K., Gao, B., and Hu, Q. F.: Impact of climate variability and human activity on streamflow decrease in the Miyun Reservoir catchment, J. Hydrol., 389, 317–324, doi:10.1016/j.jhydrol.2010.06.010, 2010.

Mann, H. B.: Non-parametric test against trend, Econometrica, 13, 245–259, 1945.

McDonald, R. I., Green, P., Balk, D., Fekete, B. M., Revenga, C., Todd, M., and Montgomery, M.: Urban growth, climate change, and freshwater availability, P. Natl. Acad. Sci. USA, 108, 6312–6317, doi:10.1073/pnas.1011615108, 2011.

Miller, J. D., Kim, H., Kjeldsen, T. R., Packman, J., Grebby, S., and Dearden, R.: Assessing the impact of urbanization on storm runoff in a pen-urban catchment using historical change in impervious cover, J. Hydrol., 515, 59–70, doi:10.1016/j.jhydrol.2014.04.011, 2014.

Mu, Q. Z., Zhao, M. S., and Running, S. W.: Improvements to a MODIS global terrestrial evapotranspiration algorithm, Remote Sens. Environ., 115, 1781–1800, doi:10.1016/j.rse.2011.02.019, 2011.

Ott, B. and Uhlenbrook, S.: Quantifying the impact of land-use changes at the event and seasonal time scale using a process-oriented catchment model, Hydrol. Earth Syst. Sci., 8, 62–78, doi:10.5194/hess-8-62-2004, 2004.

Paul, M. J. and Meyer, J. L.: Streams in the urban landscape, Annu. Rev. Ecol. Syst., 32, 333–365, 2001.

Price, K., Jackson, C. R., Parker, A. J., Reitan, T., Dowd, J., and Cyterski, M.: Effects of watershed land use and geomorphology on stream low flows during severe drought conditions in the southern Blue Ridge Mountains, Georgia and North Carolina, United States, Water Resour. Res., 47, W02516, doi:10.1029/2010wr009340, 2011.

Roderick, M. L., Hobbins, M. T., and Farquhar, G. D.: Pan evaporation trends and the terrestrial water balance. II. Energy balance and interpretation, Geogr. Compass, 3, 761–780, 2009.

Sakaguchi, A., Eguchi, S., and Kasuya, M.: Examination of the water balance of irrigated paddy fields in SWAT 2009 using the curve number procedure and the pothole module, Soil Sci. Plant Nutr., 60, 551–564, doi:10.1080/00380768.2014.919834, 2014.

Sun, G. and Lockaby, B. G.: Chapter 3: Water quantity and quality at the urban–rural interface, in: Urban–Rural Interfaces: Linking People and Nature, edited by: Laband, D. N., Lockaby, B. G., and Zipperer, W., ASACSS, SSAmerica, Madison, WI, 26–45, 2012.

Sun, G., McNulty, S. G., Lu, J., Amatya, D. M., Liang, Y., and Kolka, R. K.: Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States, J. Hydrol., 308, 258–268, doi:10.1016/j.jhydrol.2004.11.021, 2005.

Sun, G., Alstad, K., Chen, J. Q., Chen, S. P., Ford, C. R., Lin, G. H., Liu, C. F., Lu, N., McNulty, S. G., Miao, H. X., Noormets, A., Vose, J. M., Wilske, B., Zeppel, M., Zhang, Y., and Zhang, Z. Q.: A general predictive model for estimating monthly ecosystem evapotranspiration, Ecohydrology, 4, 245–255, doi:10.1002/Eco.194, 2011a.

Sun, G., Caldwell, P., Noormets, A., McNulty, S. G., Cohen, E., Myers, J. M., Domec, J. C., Treasure, E., Mu, Q. Z., Xiao, J. F., John, R., and Chen, J. Q.: Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model, J. Geophys. Res.-Biogeo., 116, G00J05, doi:10.1029/2010jg001573, 2011b.

Tang, L. H., Yang, D. W., Hu, H. P., and Gao, B.: Detecting the effect of land-use change on streamflow, sediment and nutrient losses by distributed hydrological simulation, J. Hydrol., 409, 172–182, doi:10.1016/j.jhydrol.2011.08.015, 2011.

Taylor, C. J., Pedregal, D. J., Young, P. C., and Tych, W.: Environmental time series analysis and forecasting with the captain toolbox, Environ. Modell. Softw., 22, 797–814, doi:10.1016/j.envsoft.2006.03.002, 2007.

Tsai, M. H.: The multi-functional roles of paddy field irrigation in Taiwan, Proceedings of the pre-symposium for the third world water forum (WWF3), Otsu, Shiga, Japan, 20–21 March 2002, 217–220, 2002.

Vogel, R. M. and Fennessey, N. M.: L-moment diagrams should replace product moment diagrams, Water Resour. Res., 29, 1745–1752, 1993.

Wahl, K. L. and Wahl, T. L.: Determining the Flow of Comal Springs at New Braunfels, Texas, Texas Water ’95, American Society of Civil Engineers, San Antonio, Texas, 77–86, 16–17 August 1995.

Wang, Y. J., Lv, H. J., Shi, Y. F., and Jiang, T.: Impacts of land use changes on hydrological processes in an urbanized basin: a case study in the Qinhuai River Basin, J. Nat. Resour., 24, 30–36, 2009.

Wei, X. H. and Zhang, M. F.: Quantifying streamflow change caused by forest disturbance at a large spatial scale: a single watershed study, Water Resour. Res., 46, W12525, doi:10.1029/2010wr009250, 2010.

Wu, R. S., Sue, W. R., and Chang, J. D.: A simulation model for investigating the effects of rice paddy fields on runoff system, in: MODSIM97 International Congress on Modelling and

Simulation, edited by: Zerger, A. and Argent, R. M., Modelling and Simulation Society of Australia and New Zealand, University of Tasmania, Hobart, Australia, 8–11 December 1997, 422–427, 1997.
Xiao, Y., An, K., Xie, G., and Lu, C.: Evaluation of ecosystem services provided by 10 typical rice paddies in China, J. Resour. Ecol., 2, 328–337, 2011.
Yuan, H., Dai, Y. J., Xiao, Z. Q., Ji, D. Y., and Shangguan, W.: Reprocessing the MODIS leaf area index products for land surface and climate modelling, Remote Sens. Environ., 115, 1171–1187, doi:10.1016/j.rse.2011.01.001, 2011.
Zhao, L., Lee, X., Smith, R. B., and Oleson, K.: Strong contributions of local background climate to urban heat islands, Nature, 511, 216–219, doi:10.1038/Nature13462, 2014.
Zhou, D., Zhao, S., Liu, S., Zhang, L., and Zhu, C.: Surface urban heat island in China's 32 major cities: spatial patterns and drivers, Remote Sens. Environ., 152, 51–61, 2014.

Table 1. Summary of *Z* statistics by the Nonparametric Mann–Kendall trend tests for temperature, ET, PET, and precipitation during the periods of April–October, July–August, annual LAI, Qinhuai River Basin (2000–2013).

Periods	*Z* statistic				
	LAI(*s*)	ET(*s*)	PET(*s*)	PPT(*s*)	T(*s*)
Jul–Aug	−2.41* (−0.04)	−2.30* (−1.69)	1.31(2.42)	1.31(12.93)	1.31(0.07)
Apr–Oct	−2.30* (−0.02)	−1.20 (−2.44)	2.41* (5.06)	0.11(2.63)	0.77(0.02)
Annual	−2.08* (−0.01)	−1.53 (−3.60)	2.52* (7.52)	−0.55 (−8.00)	0.00 (−0.00)

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

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

Table 2. The conversion matrix for area changes in land use and land cover during the period of 2000 to 2010 in the Qinhuai River Basin. Cropland refers to paddy field and dry crop lands.

2000 (km^2)	2010 (km^2)				
	Cropland	Forest	Water	Urban	$\sum$ (2000)
Cropland	1516	37	86	478	2116
Forest	128	98	8	37	271
Water	28	3	33	10	73
Urban	37	1	5	115	157
$\sum$ (2010)	1709	137	132	639	2617
Area change from 2000 to 2010 (km^2)	−408	−133	59	482	–
Area change from 2000 to 2010 (%)	−19	−50	81	307	–

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

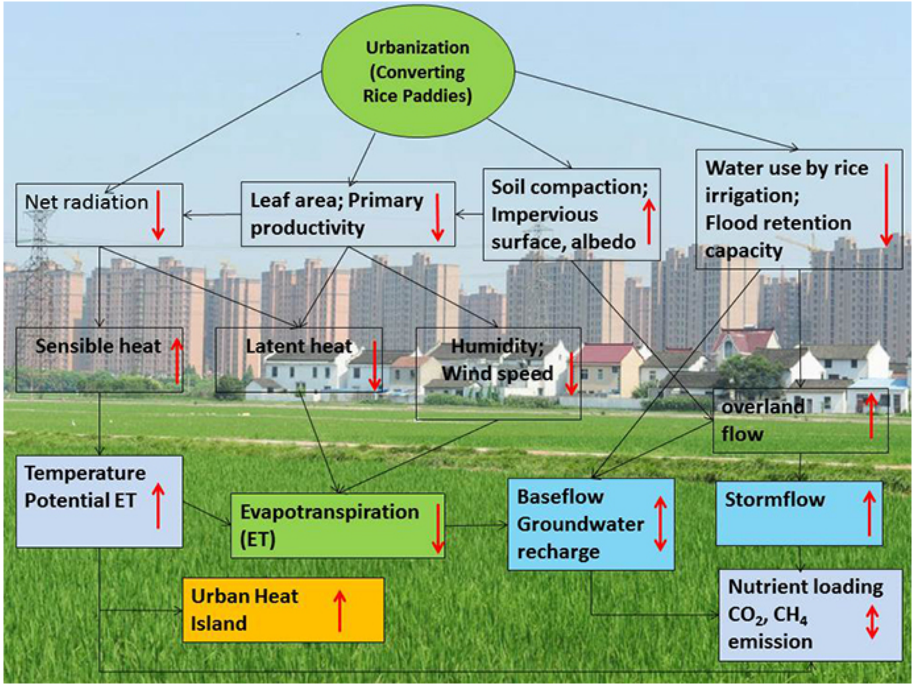

Figure 1. A conceptual model illustrating the potential hydrologic and environmental impacts of converting rice paddies to urban uses in the Yangtze River Delta region. Arrows represent directions (up or down or both) of change (Background photo credit: http://blog.sciencenet.cn/blog-578415-712508.html).

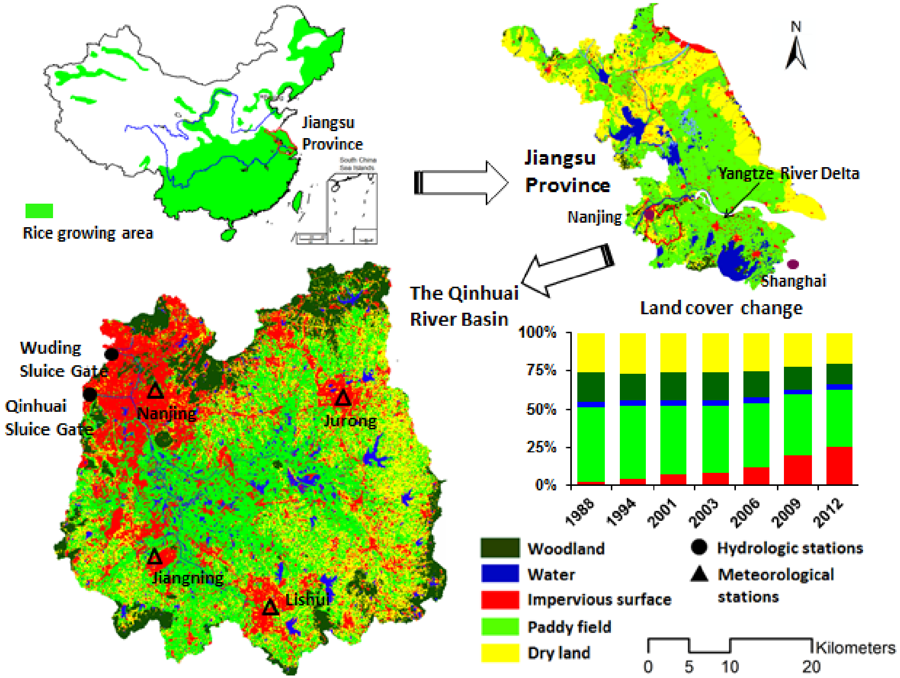

Figure 2. Watershed locations, instrumentation, and land use change from 1988 and 2012 (Du et al., 2012; Chen and Du, 2014) in the Qinhuai River Basin, Yangtze River Delta, southern China. The insert map shows land cover in the year 2012 generated from Landsat ETM+ images.

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

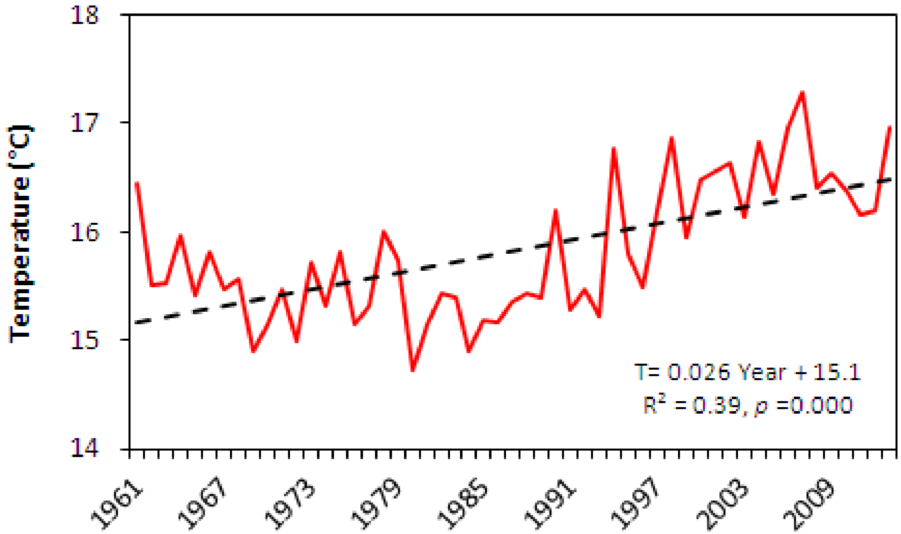

Figure 3. Mean annual air temperature change across four meteorological stations in the Qinhuai River Basin, southern China, during 1961–2013.

HESSD
12, 1941–1972, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

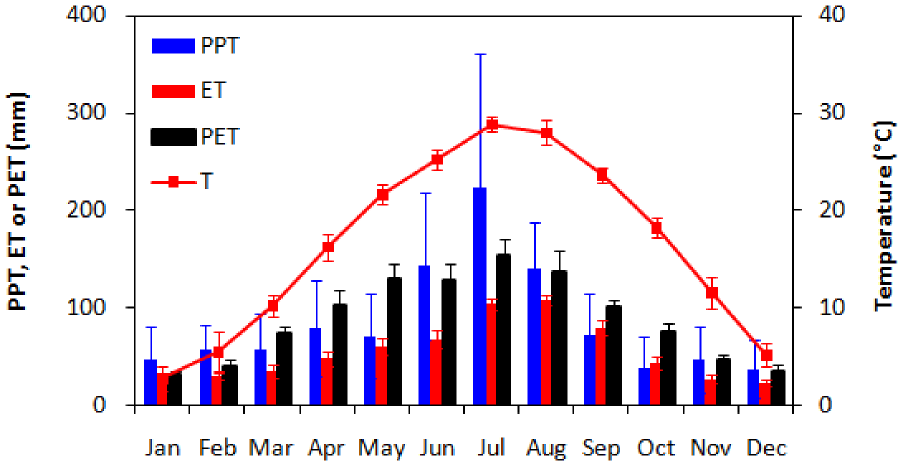

Figure 4. Mean monthly precipitation (*P*), MODIS ET, PET and temperature (*T*) (2000–2013), and the vertical lines are SD.

HESSD
12, 1941–1972, 2015

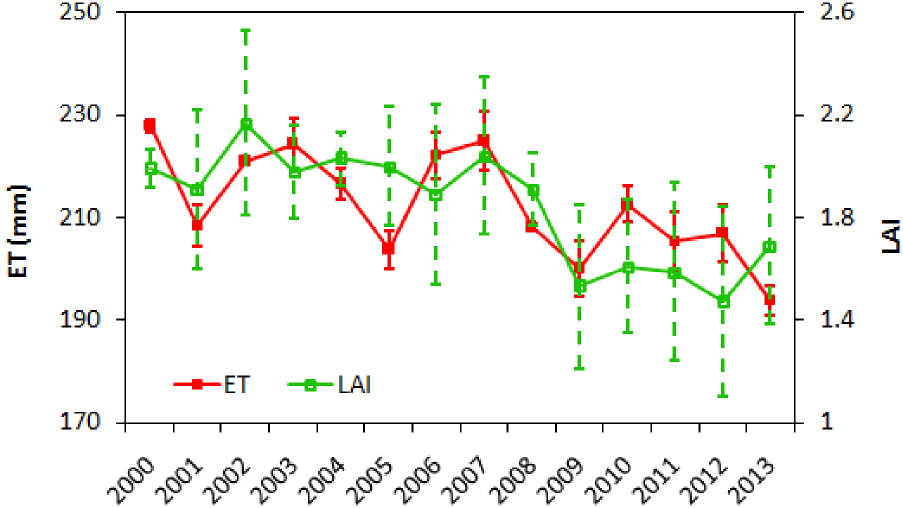

Figure 5. Changes of annual mean peak growing season (July–August) MODIS ET and LAI during 2000–2013. Vertical lines are SDs.

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

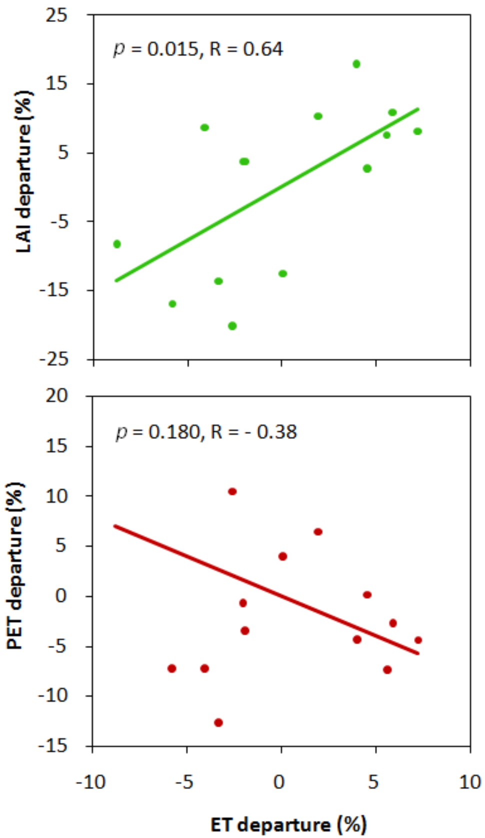

Figure 6. Correlations of the departures of basin-level ET with **(a)** the departures of mean leaf area index (LAI) and **(b)** the departures of PET in the peak growing season (July–August).

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

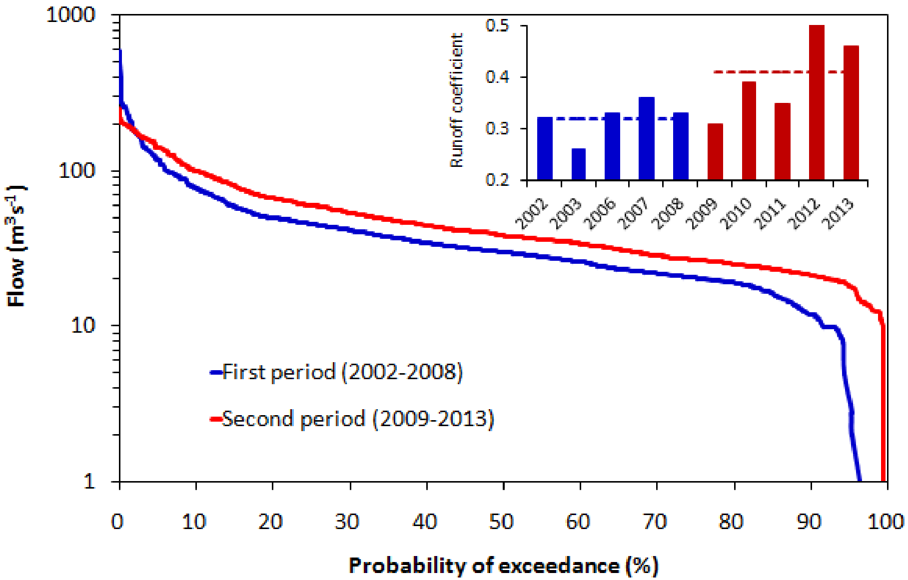

Figure 7. Flow Duration Curve for mean daily flow in the first period (2002–2003 and 2006–2008) and the second period (2009–2013) (May–October, Wuding Station) in the Qinhuai River Basin. Insert is runoff coefficient, the ratio of streamflow/precipitation for the period from May to October when the flow control gate was open.

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

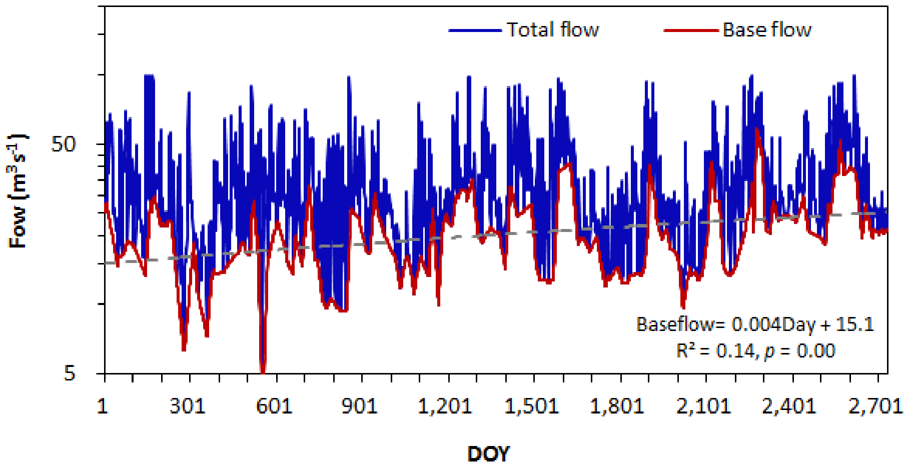

Figure 8. Trend of daily base flow separated from total stream flow measured at Wuding Station during 2006–2013. DOY is the day since 1 January 2006.

HESSD
12, 1941–1972, 2015

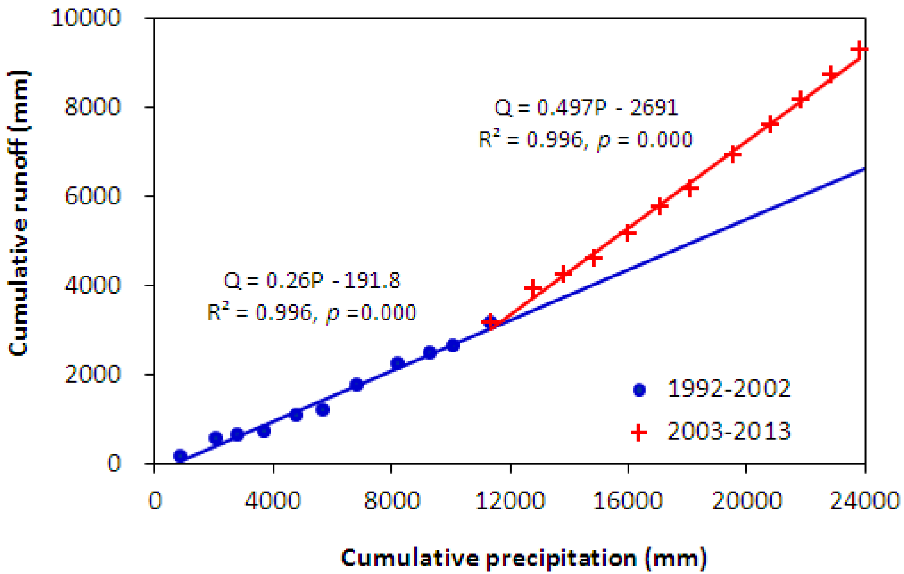

Figure 9. The Double Mass Curve showing the relations between accumulated annual precipitation (P) and total streamflow (Q) for Qinhuai River Basin (1992–2013).

HESSD
12, 1941–1972, 2015

Urbanization dramatically altered the water balances

L. Hao et al.

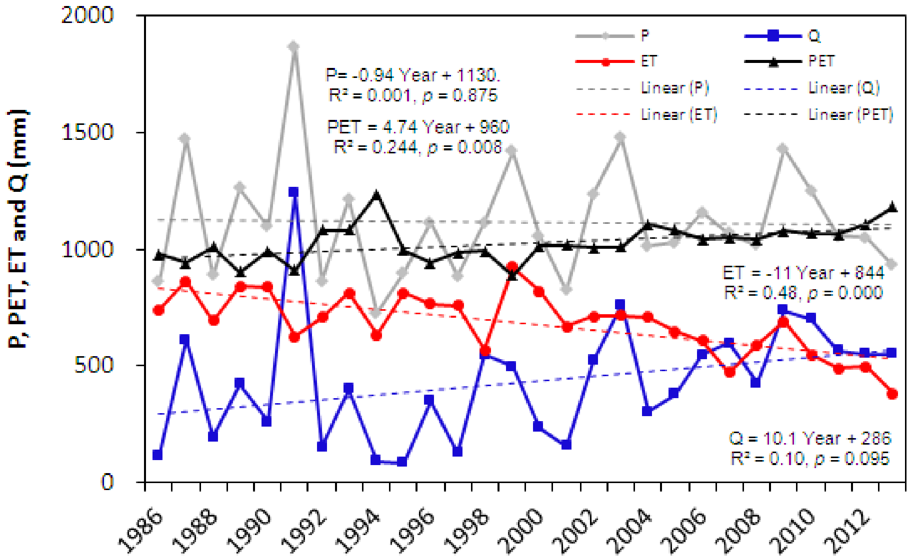

Figure 10. Trend of annual water balance and potential evapotranspiration (PET) for the Qinhuai River Basin from 1986–2013. ET was estimated as the difference between precipitation (P) and measured streamflow (Q).