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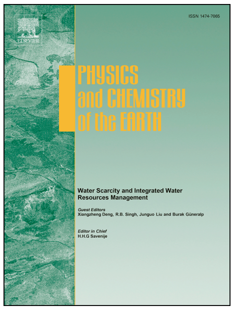

Long time-series spatiotemporal variations of NPP and water use efficiency in the Lower Heihe River Basin with serious water scarcity

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Long time-series spatiotemporal variations of NPP and water use efficiency in the Lower Heihe River Basin with serious water scarcity

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Abstract

It is of great significance to analyze the long time-series spatiotemporal dynamics of water use efficiency (WUE) to formulating appropriate management measures in response to the growing water scarcity in arid and semi-arid regions. This study analyzed the long time-series variations of WUE in the Lower Heihe River Basin, a typical arid and semi-arid region in China. The net primary productivity (NPP) was first estimated with the C-fix model, then WUE during 2001-2010 was calculated with the NPP and evapotranspiration (ET) data, and the accumulative WUE was further calculated. The results showed that the annual NPP and WUE in the study area ranged from zero to 448.70 gC/(m^2•a) and from zero to 2.20 gC kg^{-1} H_2O, respectively, both of which showed an overall increasing trend during 2001-2010. Besides, the spatial pattern of WUE kept overall unchanged during 2001-2010, but with remarkable change in some part of the study area. In addition, the accumulative WUE of the whole study area showed a first sharply decreasing and then gradually increasing trend, but there was still some scope to improve the WUE, and it is necessary to carry out some more specific policies to further improve the water allocation and WUE within the Lower Heihe River Basin. Although with some uncertainties, these results still can provide valuable reference information for improving the water resource management and ecological conservation to guarantee provision of essential ecosystem services in arid and semi-arid regions.

Key words: water use efficiency; NPP; Heihe River Basin; ecosystem services; C-fix model

1. Introduction

Decline of ecosystem services triggered by climate change and human activities is one of the most serious ecological problems in the world, especially in the arid and semi-arid regions that are very sensitive to disturbances due to the severe lack of water resources (Biggs et al., 2012; Burkhard et al., 2012; Foley et al., 2005; Ye et al., 2010). The arid and semi-arid regions are home to more than 38% of the global human population and play an important role in providing ecosystem services and guaranteeing human well-beings (Emmerich, 2003; Foley et al., 2005). However, there are numerous signs that human water use exceeds the sustainable levels (Inman-Bamber et al., 2012; Nielsen, 2003; Postel, 2000), aggravating the water scarcity and leading to considerable contradictions in water allocation in the arid and semi-arid regions around the world (Gómez-Baggethun et al., 2010; Li et al., 2015a; Molden et al., 2010). It is very necessary to study the long time-series dynamics of ecosystem services caused by the water allocation under the influence of climate change and human activities in the arid and semi-arid regions (Postel, 2000; Zhao et al., 2015). In particular, extracting water to meet human needs in the middle reach has jeopardized the health of vital ecosystems and provision of a wealth of ecosystem services in the lower reach of some inland river basins in the arid and semi-arid regions around the world (Postel, 2000; Tian et al., 2015; Yan et al., 2014), and the rational water allocation and enhancing the water use efficiency (WUE) or water productivity have been considered as the fundamental method to solve problems resulting from water scarcity (Faramarzi et al., 2010; Khare et al., 2007; Wang et al., 2012). There is a pressing need for analyzing impacts of water allocation on the provision of ecosystem services and WUE in order to provide decision support information for improving the water allocation to guarantee the provision of essential ecosystem services in these inland river basins (Faramarzi et al., 2010; Li et al., 2015b; Molden et al., 2010).

The term efficiency is generally used to quantify the relative output obtainable from a given input (Ali et al., 2007), and the WUE can be defined in various ways, depending on the nature of the inputs and outputs to be considered (Deng et al., 2014; Zhang et al., 2014b). For example, it is generally expressed as grain yield (e.g., kilograms of grain) per unit water evapotranspired (e.g., cubic meters of water and millimeters of evapotranspiration (ET)) or grain yield per unit total water input (irrigation plus rainfall) (Faramarzi et al., 2010; Singh et al., 2014). There are mainly three widely used definitions of WUE, including (1) Gross Primary Production (GPP) based WUE: GPP/ET; (2) Net Primary Productivity (NPP) based WUE: NPP/ET; (3) Net Ecosystem Production (NEP) based WUE: NEP/ET (Hu et al., 2008; Liu et al., 2015; Lu et al., 2007; Tian et al., 2010). ET is the most active process in the hydrological cycle and is also a major component of energy and water balance in agriculture ecosystems, and it is widely assumed to be the water consumed by vegetation to provide the ecosystem services (Burba and Verma, 2005; Oki and Kanae, 2006).

Net primary productivity (NPP) lays the foundation for provision of various ecosystem services and is essential to the human well-being of local and regional people (Feng et al., 2001; Xiao and Cheng, 2006), it is of great significance to analyze the spatiotemporal dynamics of NPP based WUE (Koschke et al., 2014; Peng and Apps, 1999; Zhang et al., 2010). Numerous models have been developed for estimating NPP at global or regional scales, which can be generally categorized into climate-related models, light use efficiency models and process-based models

(Mu et al., 2013; Peng and Apps, 1999). The climate-related and process-based models have been widely used in previous studies. However, the climate-related models (e.g., the Miami model) can only estimate the potential vegetation productivity (Wu et al., 2013a; Yan et al., 2015), while the process-based models (e.g., the LPJ-GUESS model) can only simulate the dynamics of natural vegetation under certain climatic conditions, thus making these models unsuitable for estimating NPP in regions with extensive human activities (Faramarzi et al., 2010; Pappas et al., 2015). In contrast, parameter models (e.g., the C-fix model) can accurately estimate NPP with real time remote sensing data and have been widely used to study the spatiotemporal dynamics of NPP (Peng and Apps, 1999; Veroustraete et al., 2002; Zhang et al., 2014b).

There have been over 20 major inter-basin water diversion projects to improve the water allocation in China (Liu et al., 2013), one of which is the Ecological Water Diversion Project in the Heihe River Basin, the second largest inland river basin in China (Hu et al., 2015; Mu et al., 2013; Wang et al., 2015c). A number of studies have mapped the provision of ecosystem services and estimated their economic values in the Heihe River Basin, however, there is still a broad knowledge gap about the influence of water diversion on provision of ecosystem services and WUE in the Lower Heihe River Basin after over ten years of water diversion (Lu et al., 2005; Shi et al., 2014; Song et al., 2015a; Wang et al., 2015c; Yan et al., 2014). In particular, the long time-series spatiotemporal variation of ecosystem services can provide valuable information for improving the local water management and ecological conservation, but there is still lack of long time-series information of the provision of ecosystem services in this region. There are urgent calls at the basin level for quantitative studies on the long time-series provision of ecosystem services and WUE in the lower reach to provide sufficient supporting information for promoting the rational water allocation and improving the WUE as a way to mitigate water scarcity in this river basin (Liu et al., 2005). With the objective to provide a sound scientific foundation for improving water resource management and ecological conservation, this study analyzed the long time-series spatiotemporal variation of NPP and WUE in the Lower Heihe River Basin. The C-fix model was first calibrated and used to estimate NPP during 2001-2010, then the WUE was estimated with the NPP and ET data. Finally, management implications were discussed. The results of this study can provide valuable spatiotemporal information for improving the water resource management and ecological conservation to guarantee sustainable provision of essential ecosystem services.

2. Methods and materials

2.1. Study area

The Heihe River Basin is a typical inland river basin in the arid and semi-arid region of China, the middle reach of which is an important grain production base and the lower reach is an important pastoral region and serves as an important ecological barrier of the northern part of China. The Lower Heihe River Basin is located between 97.13°-103.12° E and 39.87°-42.79° N, with the total land area of approximately 7.71×10^4 km^2 (Fig. 1). The plain accounts for approximately 60% of the total area of this region, with the altitude ranging from 869 to 1885 m. The local vegetation mainly includes grassland and forests, there is some cropland in the oases such as Ejina Oasis, and most part of this region is covered by unused land such sandy land and Gobi. However, there is one of the largest Populus Euphratica forests of the world in Ejina Banner, which serves as the first ecological barrier to intercept sandstorms into China and plays an important role in guaranteeing the ecological safety of the northern part of China (Yan et al., 2014). In the Lower Heihe River Basin, the average annual precipitation is only 37 mm while the annual ET is above 1000 mm, making this region extremely dry and sensitive to climate change and human activities. The runoff of the Heihe River plays a key role in supplementing the groundwater and sustaining the local ecosystems in the Lower Heihe River Basin (Xiao and Cheng, 2006). Unfortunately, the spatiotemporal dynamics of water resources in the Heihe River Basin has changed greatly under the influence of climate change and human activities during past decades. The water overexploitation in the middle reach greatly reduced the runoff into the lower reach during past decades, posing a great threat to the provision of essential ecosystem services such as primary production and soil conservation in the lower reach (Kang et al., 2007; Yan et al., 2014). To address the severe ecological degradation and guarantee the provision of essential ecosystem services in the Lower Heihe River Basin, the Chinese government carried out the Ecological Water Diversion Project was implemented in 2000.

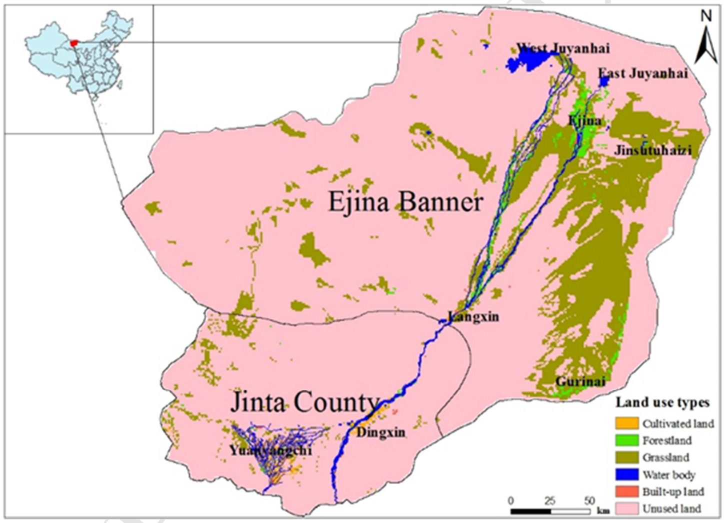

Fig. 1. Location and land use of the Lower Heihe River Basin in 2010.

2.2. Estimation of NPP and WUE

Since it is difficult to directly measure NPP in a large area, this study estimated NPP with the C-fix model (Veroustraete et al., 2002), one of the widely used light use efficiency models. The C-fix model is driven by temperature, radiation, fraction of Absorbed Photosynthetically Active Radiation (*fAPAR*) and carbon dioxide (CO_2) concentration (Veroustraete et al., 2002). It quantifies NPP as a function of absorbed photosynthetically active radiation (APAR) and light use efficiency of vegetation types as follows.

$$NPP_d = [p_{(T_{atm})} \times CO_2 fert \times \varepsilon \times fAPAR \times c \times S_{g,d}] \times (1 - A_d) \qquad (1)$$

where NPP_d is the daily NPP, $p_{(Tatm)}$ is the normalized temperature dependency factor, which was calculated with the method described by Wang et al. (Wang, 1996), CO_2fert is the normalized CO_2

fertilization factor estimated with the air temperature and CO_2 concentration (Veroustraete et al., 2002), ε is the radiation use efficiency, which is 1.10 (gC/MJ) in the original C-fix model, and in this study its values for major vegetation types were assigned with the parameter values of Running et al. (2000) on the basis of land use data. $fAPAR$ is the fraction of Absorbed Photosynthetically Active Radiation, which is calculated as a linear function of the Normalized Difference Vegetation Index (NDVI) (Fensholt et al., 2004). c is the climatic efficiency giving the ratio of PAR to global radiation, which is 0.48 (Veroustraete et al., 2002); $S_{g,d}$ is the daily incoming global solar radiation, which was obtained from the daily meteorological observation data; A_d is the autotrophic respiratory fraction of gross primary productivity, which is estimated as $A_d=(7.825+1.145\times T_a)/100$, where T_a is the air temperature (Unit: °C) (Goward and Dye, 1987). More details can be found in literatures (Lu et al., 2005; Veroustraete et al., 2002).

The WUE measures the net return for a unit of water used, and NPP/ET has been widely used to calculate the WUE of the primary production (Molden et al., 2010; Tian et al., 2010), and in this study the WUE was calculated with the annual NPP and annual ET as follows.

$$WUE = NPP / ET \tag{2}$$

where WUE is the water use efficiency (Unit: gC/kg H_2O), NPP (Unit: $gC/(m^2 \bullet a)$) and ET (Unit: mm•a) is the annual NPP and ET in a specific grid cell, respectively. Additionally, the accumulative WUE of the whole study area was calculated in a similar way with the accumulative NPP and ET.

2.3. Data collection and processing

A database for estimating NPP and WUE was built, mainly covering the climate data, land use data, NDVI data and ET data during 2001 and 2010, all of which were processed with the same spatial reference and resolution. Climate data included daily air temperature, daily solar radiation, and monthly CO during 2001-2010. The daily air temperature and solar radiation data were derived from daily records of meteorological stations maintained by the China Meteorological Administration in the study area and neighborhood regions. The daily air temperature and solar radiation data were originally saved in form of text and were then interpolated into 1 km resolution grid data using gradient plus inverse distance squares method (Wu et al., 2013b; Zhan et al., 2010). The daily temperature data were further adjusted with the 1km resolution digital elevation model (DEM) and monthly temperature lapse rates provided by Heihe Plan Science Data Center since temperature decreases with the altitude. The monthly CO_2 concentration data were downloaded from the website http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html and were further converted into grid data. Besides, the land use data were derived from Landsat TM/ETM images in 2000, 2005, 2008 and 2010, which was interpreted by Chinese Academy of Sciences, with the overall interpretation accuracy of 92.7% (Deng et al., 2010; Liu et al., 2005). In addition, the NDVI data were also provided by Heihe Plan Science Data Center, which were then used to calculate $fAPAR$ (Fensholt et al., 2004; Li and Jie, 2013). The ET data and the runoff data of the Heihe River in the Zhengyixia Station were provided by Heihe Plan Science Data Center (Wu et al., 2012).

3. Results and discussion

3.1. Model validation and uncertainties

The results from the C-fix model showed that NPP in the Lower Heihe River Basin ranged from zero to 448.70 gC/(m^2•a) (Fig. 2), with the average NPP ranging between 20.77 and 33.19 gC/(m^2•a) during 2001-2010, both of which fall within the ranges in previous studies (Lu et al., 2005; Zhang et al., 2014a; Zhou et al., 2013). For example, the mean NPP of forest land from the C-fix model (102.37-178.10) is consistent with of the results of Zhang et al. (2014a) (103.06-187.59), while the average NPP of cultivated land in this study (157.02 $gC\cdot m^{-2}\cdot a^{-1}$) was only slightly lower than that of Zhang et al. (2014a) (170.76 $gC\cdot m^{-2}\cdot a^{-1}$) and MOD17 (174.57 $gC\cdot m^{-2}\cdot a^{-1}$). Besides, the WUE in the Lower Heihe River Basin ranged from zero to 2.20 gC kg^{-1} H_2O during 2001-2010, with an average of approximately 0.29 gC kg^{-1} H_2O, which is consistent with results in previous studies (Liu et al., 2015; Lu et al., 2007). Overall, there are still some differences between the results in this study and previous studies, which may be due to differences in the spatial extent of the study area, data sources and so on, but the results of this study still agree well with that of previous studies.

There are inevitably some uncertainties in the results due to the model parameters, input data and model algorithms and so on since both NPP and ET are influenced by very complex processes and various interactive factors. First, the parameters in the C-fix model have been adjusted according to the previous literatures and local conditions of the study area, but they may be not perfectly suitable for the study area, which may lead to biases in the estimated NPP. Besides, the model algorithms may also contribute to uncertainties in the estimated NPP, for example, the water limitation is not explicitly modelled in the in C-fix model, which is only implicitly involved by assimilation of *fAPAR* (Veroustraete et al., 2002; Verstraeten et al., 2006). In addition, although most input data are from available data sources that have been validated, the data accuracy may still contribute to the uncertainties in the estimation of NPP and WUE. For example, the climate data were obtained by interpolating daily observation data from meteorological stations, but there are only a few meteorological stations within and around the study area, which may lead to some bias in the interpolated climate data and subsequently estimated NPP. In particular, the ET data used in this study may have been slightly overestimated according to the comparison with other ET data (Jia et al., 2013; Wu et al., 2012), which may lead to slight underestimation of the WUE. Moreover, all the data were processed at 1km resolution in this study, which may be not precise enough to accurately reveal the spatial heterogeneity of characteristics of the seriously fragmented landscapes in this region. It is necessary to estimate NPP with more accurate data and evaluate the ecosystem models against ground and satellite-based measurements and observations in order to improve the estimation accuracy, but even with some uncertainties, the results of this study still suggests it is still feasible to analyze the effects of water allocation on NPP and WUE based on the results from the C-fix model.

3.2. Spatiotemporal variation of NPP

The spatial pattern of NPP kept generally unchanged during 2001-2010, with remarkable change in only a few part of the study area (Fig. 2). In 2001, regions with annual NPP above 150 gC/(m^2•a) concentrated in the core part of oases, where there is mainly cultivated land and forest land, and the annual NPP declined to 50-150 gC/(m^2•a) in the fringe of oases and regions near the Heihe River and Gurinai Lake. By comparison, the annual NPP reached only 20-50 gC/(m^2•a) in the northwest and southeast part of the study area, where there was mainly sandy land and low-coverage grassland, while it was generally below 20 gC/(m^2•a) in most part of the study area, where the major land use types were sandy land and Gobi. The annual NPP showed remarkable change in a few part of the study area during 2001-2010. For example, the regions with NPP above 150 gC/(m^2•a) expanded obviously in Yuanyangchi Oasis and Dingxin Oasis in Jinta County in 2010, and the annual NPP in regions between these two oases showed noticeable increase. By comparison, the spatial pattern of NPP showed no obvious change in most part of Ejina Banner except East Juyanhai Lake in 2010 (Fig. 2).

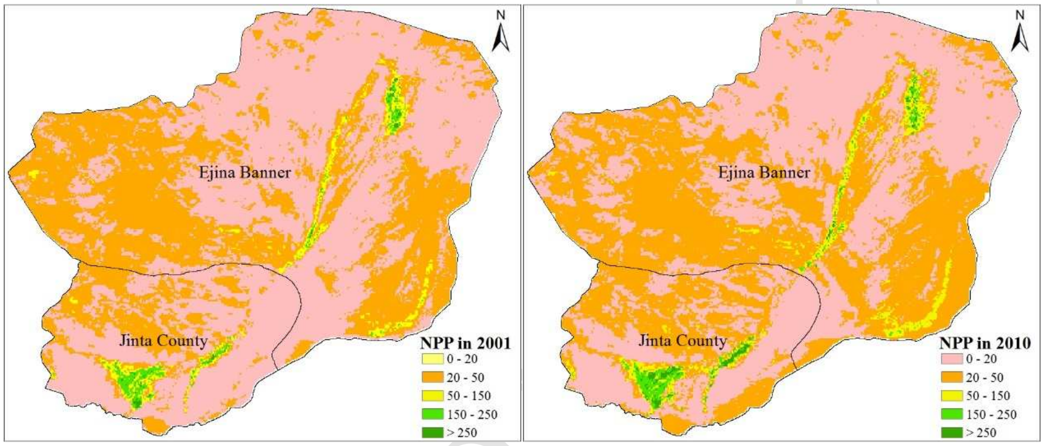

Fig. 2. Spatial pattern of the annual NPP (Unit: gC/(m^2•a)) in the Lower Heihe River Basin in 2001 and 2010.

3.3. Spatiotemporal variation of ET and WUE

The annual ET in the Lower Heihe River Basin ranged from less than 20 mm to over 1400 mm, the spatial pattern of which kept overall unchanged during 2001-2010 (Fig. 3). For example, the annual ET above 150 mm concentrated in the oases, East Juyanhai, regions along the mainstream of Heihe River and a few region near Gurinai Lake in 2001. The highest ET generally occurred in the forests, water bodies as well as cultivated land, and the annual ET of the water body generally exceeded 1000 mm. While the annual ET was very low in most part of the study area, ranging between 50-75 mm in most part of Ejina Banner and 75-100mm in most part of Jinta County. The lowest ET was found in deserts and Gobi, e.g., some mountainous regions in the northwest part of the study area. Besides, the annual ET increased to some extent in most part of the study area during 2001-2010, but its overall spatial pattern kept unchanged, with obvious change in only a few part of the study area. For example, the annual ET increased significantly in East Juyanhai Lake and Jinsutuhaizi Lake, where the water body expanded significantly after years of water diversion (Fig. 3).

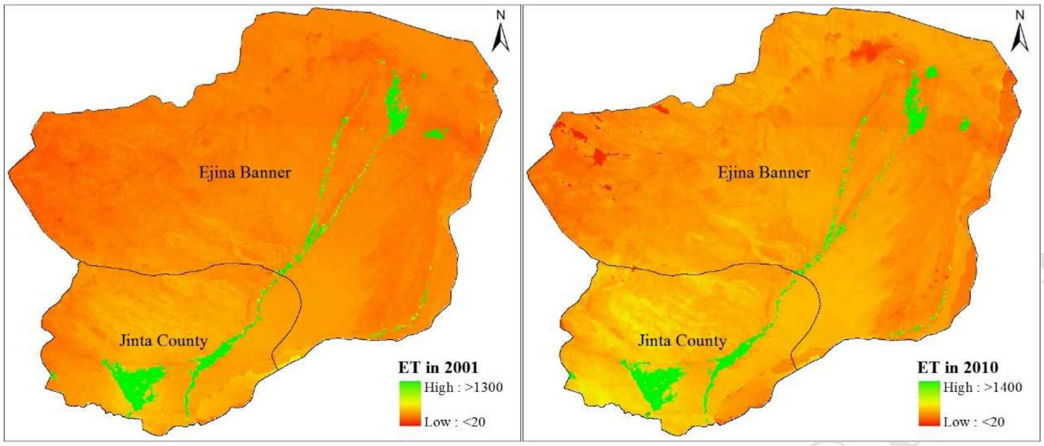

Fig. 3. Spatial variation of ET (Unit: mm) in the Lower Heihe River Basin in 2001 and 2010.

The spatial pattern of WUE kept unchanged in most part of the study area during 2001-2010, which was generally high in the high vegetation coverage regions such as the oasis and lower in low vegetation coverage regions such as Gobi and sandy land far from the Heihe River (Fig. 4). The WUE showed a spatial pattern similar to that of NPP and ET, but with some differences in the northwest and southeast part of the study area where the major vegetation types were shrub, low-coverage grassland and desert plants. The desert plants may have high WUE under water deficit conditions (Lu et al., 2007), and in these regions the annual NPP was low but the annual ET was even lower, resulting in high WUE. This indicated that both the water availability and vegetation composition had important influence on the WUE. Besides, there was some significant change in the WUE in some regions in the northwest and south part of the study area during 2001-2010. For example, the WUE showed widespread decline in the northwest part of the study area, where there are water scarce mountainous regions that are very sensitive to climate change. Meanwhile the WUE showed widespread increase in Yuanyangchi Oasis, Dingxin Oasis and regions between them in Jinta County. The annual NPP increased significantly in these regions during 2001-2010, while the annual ET declined in most part of these regions, which may be due to the technical progress in agricultural irrigation (Wang et al., 2015a; Zhou et al., 2015). However, the increase and decrease of WUE coincided in Ejina Banner (Fig. 4). On the one hand, the increase of runoff of the Heihe River increased the available water, which further increased both NPP and ET in this region. On the other hand, the local human activities changed the vegetation coverage and consequently led to the coincident increase and decrease of the WUE. In particular, the WUE declined obviously in regions near East Juyanhai Lake and Jinsutuhaizi Lake, which was mainly due to sharp increase of ET caused by the expansion of water bodies after years of water diversion.

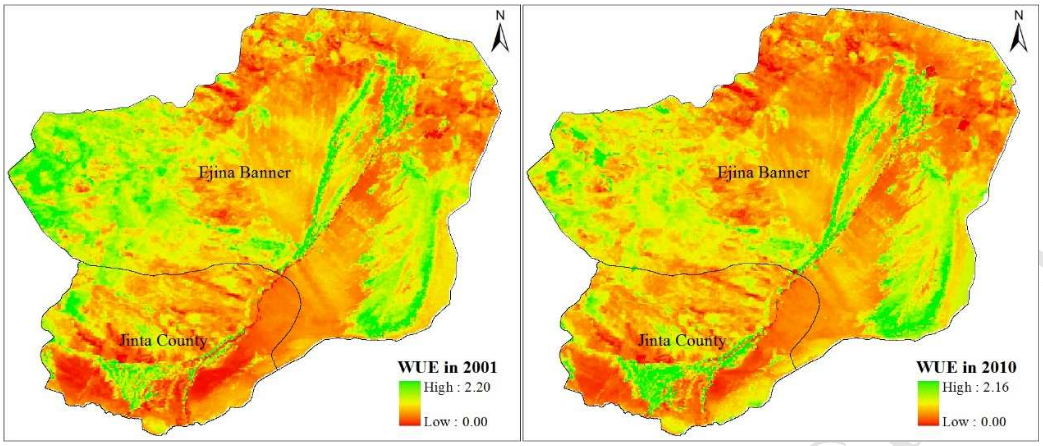

Fig. 4. Spatial pattern of the WUE (Unit: gC kg^{-1} H_2O) in the Lower Heihe River Basin in 2001 and 2010.

3.4. Impacts of runoff on ET, NPP and WUE

The runoff of the Heihe River played a key role in influencing ET in the study area, where there is very limited annual precipitation, and the annual runoff volume increased obviously during 2001-2003 and kept overall stable during 2004-2009 but declined in 2010, showing an overall increasing trend during the entire study period (Fig. 5). However, the variation of the total annual ET of the study area was not synchronous with the runoff, showing no obvious changing patterns during 2001-2010 (Fig. 5). Besides, the accumulative runoff and ET during 2001-2010 were further calculated, and the results showed that both of them showed an increasing trend. However, the slope of the curve of the accumulative runoff was much higher than of that of the accumulative ET, which was 11.12 and 6.51, respectively, indicating that the increasing rate of accumulative ET was much lower than that of the accumulative runoff (Fig. 5). In fact, the annual ET was influenced by not only the runoff but also other factors such as climate and land use change in the study area. More importantly, the runoff provided available water for not only ET, but also the groundwater supplementation, and a large proportion of runoff was used to supplement the groundwater during the study period (Wang et al., 2014; Wang et al., 2011).

Fig. 5. Annual and accumulative runoff and ET (Unit: 10^9 m^3) in the Lower Heihe River Basin during 2001-2010.

The total annual NPP of the study area was between 1.58 and 2.09 * 10^{12} gC/a and showed an overall increasing trend during 2001-2010, and the accumulative NPP of the whole study area showed a slope of 1.88, which was much lower than that of the accumulative runoff and ET (Fig.

6). By comparison, the average WUE of the study area ranged between 0.25 and 0.33 gC kg^{-1} H_2O and showed only slight overall change during 2001-2010, which is mainly because the water diversion can influence the WUE in regions near the Heihe River while the vegetation structure of the whole study kept overall unchanged during the entire study period. In particular, the accumulative WUE of the whole study area declined sharply during 2001-2002 and showed an increasing trend since 2002 (Fig. 6). The annual runoff increased significantly from 6.31 * 10^9 m^3 in 2001 to 9.33 * 10^9 m^3 in 2002, which led to rapid increase of ET. But there was one year lag of the response of the vegetation dynamics and NPP to runoff change and not all the runoff was used by the vegetation, consequently leading to the sharp decrease of WUE during 2001-2002. Nevertheless, the water diversion had overall positive accumulative effects on NPP and WUE, which may be because more water was used by the vegetation after the groundwater was effectively supplemented after 2002.

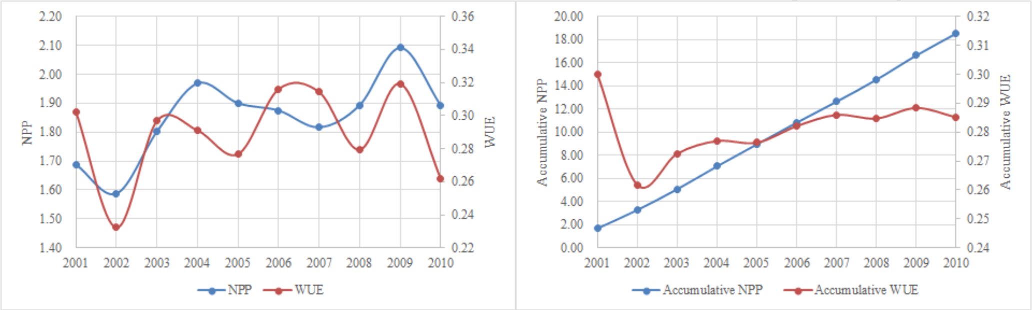

Fig. 6. Annual and accumulative NPP (Unit: 10^{12} gC/a) and WUE (Unit: gC/kg H_2O) of the Lower Heihe River Basin during 2001-2010.

3.5. Management implications

The average WUE of the study area increased after 2002, but it was still lower than it was in 2001, indicating that there was still some scope to improve the WUE, however, the question of how to improve WUE is rather complex given the local agronomic, hydrogeological and socio-economic conditions (Faramarzi et al., 2010). It has been reported that uneven changes in environmental factors can lead to spatially heterogeneous responses of WUE (Tian et al., 2010). The land use and land cover change (LUCC) and climate change are among the primary driving forces for terrestrial ecosystem productivity and water availability (Deng et al., 2015b; Liu et al., 2013; Yin et al., 2014; Zhang et al., 2014b). Climate change and LUCC in the upper and middle reach influenced the total runoff into the lower reach and indirectly influenced the WUE in this region (Deng et al., 2015a; Jin et al., 2015), but climate change and LUCC within the lower reach played a more important role in influencing NPP and WUE of the study area (Deng et al., 2013; Song et al., 2015b). On the one hand, the runoff into the study area increased since 2001, but meanwhile the oases in Jinta County expanded, increasing the runoff for agricultural irrigation and consequently reducing the runoff into Ejina Banner (Song and Zhang, 2015; Wang et al., 2015b). For example, the runoff into the lower reach was approximately 9.91 * 10^9 m^3 in 2010, but 4.06 * 10^9 m^3 out of which was consumed in Jinta County, only approximately 5.79 * 10^9 m^3 finally entered Ejina Banner, which may greatly lessen the final effects of the Ecological Water Diversion Project. On the other hand, the water bodies in Ejina Banner expanded obviously since 2001, where the ET consumed considerable amount of water resources. For example, previous study showed that the annual ET of lakes in Ejina Banner increased from 0.18 * 10^9 m^3 in 2002 to 1.79 * 10^9 m^3 in 2010 (Liao et al., 2015), and results in this study also suggested that the annual ET of East Juyanhai Lake and Jinsutuhaizi Lake in Ejina Banner reached 1.20 * 10^9 m^3 in 2010, with a much higher increasing rate than that of the whole study area. It is therefore not surprising that there was no significant change in the total NPP and overall WUE in Ejina Banner since the proportion of runoff for vegetation recovery was not high in fact.

The annual runoff declined in 2010 (Fig. 5), and meanwhile the total annual NPP and accumulative WUE of the whole study area also decreased (Fig. 6), indicating that the influence of internal factors of the study area on the WUE has kept overall unchanged. The WUE can only be increased by increasing the runoff if internal factors such as the vegetation structure and land use pattern in the study area kept unchanged, however, it has been difficult to further increase the runoff into the lower reach. It is therefore only feasible to further improve the WUE by adjusting the internal factors of the lower reach. For example, it is necessary carry out some water allocation schemes to coordinate the trade-offs between Jinta County and Ejina Banner and tip the balance between the ecological and economic water uses in these two regions. It is also urgent for the local and regional ecosystem managers and policy makers to carry out some policies that can further promote the WUE by adjusting the local vegetation structure and land use patterns in Ejina Banner. For example, it may be more beneficial to expand the grassland with lower ET rather than water bodies with high ET in Ejina Banner, and the limited water resources should be allocated for ecosystem rehabilitation rather than reclamation of new cultivated land (Cheng et al., 2014). Overall, more policies should be formulated according to the local conditions to further improve the water allocation in order to guarantee the provision of essential ecosystem services.

4. Conclusions

It is of great importance to study the spatiotemporal dynamics of NPP and WUE in order to formulate appropriate management measures that will guarantee the sustainable provision of essential ecosystem services. In this study, the NPP in the lower Heihe River Basin during 2001-2010 was estimated with the C-fix model, and then the WUE was estimated with the NPP and ET data. The long time-series variations of annual and accumulative NPP and WUE were further analyzed, which can provide valuable spatially explicit information for supporting the decision-making and ecological conservation.

The annual NPP and WUE in the study area ranged from zero to 448.70 gC/(m^2•a) and from zero to 2.20 gC kg^{-1} H_2O, respectively, both of which showed an overall increasing trend with some fluctuation during 2001-2010. Besides, the annual NPP and WUE showed a similar spatial pattern, which kept overall unchanged but with remarkable change in some part of the study area during 2001-2010. In addition, the accumulative NPP of the whole study area showed a slope of change of 1.88, which was much lower than that of the accumulative runoff and ET. While the accumulative WUE of the whole study area declined sharply during 2001-2002 and then showed an increasing trend, it was still lower than that in 2001, suggesting there is still some scope to improve the WUE. What’s more, the water diversion had positive accumulative effects on both NPP and WUE of the study area, but it is urgent to take measures to improve the WUE by adjusting internal factors within this region. In particular, it is necessary to carry out some more specific policies to improve the water allocation between Jinta County and Ejina Banner. Although with some uncertainties, these results still can provide valuable reference information for the water resource management and ecological conservation to improve the WUE and guarantee the provision of essential ecosystem services.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Ali, M.H., Hoque, M., Hassan, A., Khair, A., 2007. Effects of deficit irrigation on yield, water productivity, and economic returns of wheat. Agricultural Water Management 92, 151-161.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E.L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T.M., Evans, L.S., Kotschy, K., 2012. Toward principles for enhancing the resilience of ecosystem services. Annual Review of Environment and Resources 37, 421-448.

Burba, G.G., Verma, S.B., 2005. Seasonal and interannual variability in evapotranspiration of native tallgrass prairie and cultivated wheat ecosystems. Agricultural and Forest Meteorology 135, 190-201.

Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply, demand and budgets. Ecological Indicators 21, 17-29.

Cheng, G., Li, X., Zhao, W., Xu, Z., Feng, Q., Xiao, S., Xiao, H., 2014. Integrated study of the water–ecosystem–economy in the Heihe River Basin. National Science Review.

Deng, X., Huang, J., Rozelle, S., Zhang, J., Li, Z., 2015a. Impact of urbanization on cultivated land changes in China. Land Use Policy 45, 1-7.

Deng, X., Jiang, Q.o., Zhan, J., He, S., Lin, Y., 2010. Simulation on the dynamics of forest area changes in Northeast China. Journal of Geographical Sciences 20, 495-509.

Deng, X., Li, Z., Huang, J., Shi, Q., Li, Y., 2013. A revisit to the impacts of land use changes on the human wellbeing via altering the ecosystem provisioning services. Advances in Meteorology 2013.

Deng, X., Shi, Q., Zhang, Q., Shi, C., Yin, F., 2015b. Impacts of land use and land cover changes on surface energy and water balance in the Heihe River Basin of China, 2000–2010. Physics and Chemistry of the Earth, Parts A/B/C 79-82, 2-10.

Deng, X., Zhang, F., Wang, Z., Li, X., Zhang, T., 2014. An extended input output table compiled for analyzing water demand and consumption at county level in China. Sustainability 6, 3301-3320.

Emmerich, W.E., 2003. Carbon dioxide fluxes in a semiarid environment with high carbonate soils. Agricultural and Forest Meteorology 116, 91-102.

Faramarzi, M., Yang, H., Schulin, R., Abbaspour, K.C., 2010. Modeling wheat yield and crop water productivity in Iran: Implications of agricultural water management for wheat production. Agricultural Water Management 97, 1861-1875.

Feng, Q., Cheng, G.D., Endo, K.N., 2001. Towards sustainable development of the environmentally degraded River Heihe basin, China. Hydrological Sciences Journal 46, 647-658.

Fensholt, R., Sandholt, I., Rasmussen, M.S., 2004. Evaluation of MODIS LAI, fAPAR and the relation between fAPAR and NDVI in a semi-arid environment using in situ measurements. Remote sensing of Environment 91, 490-507.

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., 2005. Global consequences of land use. science 309, 570-574.

Gómez-Baggethun, E., De Groot, R., Lomas, P.L., Montes, C., 2010. The history of ecosystem services in economic theory and practice: from early notions to markets and payment schemes. Ecological Economics 69, 1209-1218.

Goward, S.N., Dye, D.G., 1987. Evaluating North American net primary productivity with satellite observations. Advances in Space Research 7, 165-174.

Hu, X., Lu, L., Li, X., Wang, J., Lu, X., 2015. Ejin Oasis land use and vegetation change between 2000 and 2011: The role of the Ecological Water Diversion Project. Energies 8, 7040-7057.

Hu, Z., Yu, G., Fu, Y., Sun, X., Li, Y., Shi, P., Wang, Y., Zheng, Z., 2008. Effects of vegetation control on ecosystem water use efficiency within and among four grassland ecosystems in China. Global change biology 14, 1609-1619.

Inman-Bamber, N., Lakshmanan, P., Park, S., 2012. Sugarcane for water-limited environments: Theoretical assessment of suitable traits. Field Crops Research 134, 95-104.

Jia, L., Hu, G., Cui, Y., 2013. The evapotranspiration data from 2009 to 2011 in the Heihe River Basin. Heihe Plan Science Data Center.

Jin, G., Wang, P., Zhao, T., Bai, Y., Zhao, C., Chen, D., 2015. Reviews on land use change induced effects on regional hydrological ecosystem services for integrated water resources management. Physics and Chemistry of the Earth, Parts A/B/C 89-90, 33-39.

Kang, E., Lu, L., Xu, Z., 2007. Vegetation and carbon sequestration and their relation to water resources in an inland river basin of Northwest China. Journal of Environmental Management 85, 702-710.

Khare, D., Jat, M., Sunder, J., 2007. Assessment of water resources allocation options: conjunctive use planning in a link canal command. Resources, conservation and recycling 51, 487-506.

Koschke, L., Lorz, C., Fürst, C., Lehmann, T., Makeschin, F., 2014. Assessing hydrological and provisioning ecosystem services in a case study in Western Central Brazil. Ecological Processes 3, 1-15.

Li, H., Li, Z., Li, Z., Yu, J., Liu, B., 2015a. Evaluation of ecosystem services: A case study in the middle reach of the Heihe River Basin, Northwest China. Physics and Chemistry of the Earth, Parts A/B/C 89-90, 40-45.

Li, J., Jie, Z., 2013. The cloud-free NDVI data from 2001 to 2011 in the Heihe River Basin. Heihe Plan Science Data Center.

Li, Z., Deng, X., Wu, F., Hasan, S.S., 2015b. Scenario analysis for water resources in response to land use change in the Middle and Upper Reaches of the Heihe River Basin. Sustainability 7, 3086-3108.

Liao, J., Wang, T., Xue, X., 2015. Lake's evaporation in the Ejin Basin since Transfering Water from the Heihe River. Journal of Desert Research 35, 228-232.

Liu, J., Zang, C., Tian, S., Liu, J., Yang, H., Jia, S., You, L., Liu, B., Zhang, M., 2013. Water conservancy projects in China: Achievements, challenges and way forward. Global Environmental Change 23, 633-643.

Liu, J., Zhan, J., Deng, X., 2005. Spatio-temporal patterns and driving forces of urban land expansion in China during the economic reform era. AMBIO: a journal of the human environment 34, 450-455.

Liu, Y., Xiao, J., Ju, W., Zhou, Y., Wang, S., Wu, X., 2015. Water use efficiency of China’s terrestrial ecosystems and responses to drought. Scientific Reports 5, 1-12.

Lu, L., Li, X., Frank, V., 2005. Estimation of net primary productivity of heihe river basin using remote sensing. Journal of Desert Research 25, 823-830.

Lu, L., Li, X., Huang, C., Veroustraet, F., 2007. Using remote sensing to estimate water use efficiency in Western China, Geoscience and Remote Sensing Symposium, 2007. IGARSS 2007. IEEE International. IEEE, pp. 4538-4541.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agricultural Water Management 97, 528-535.

Mu, S., Zhou, S., Chen, Y., Li, J., Ju, W., Odeh, I., 2013. Assessing the impact of restoration-induced land conversion and management alternatives on net primary productivity in Inner Mongolian grassland, China. Global and Planetary Change 108, 29-41.

Nielsen, D.C., 2003. Water in Dryland Cropping Systems, Colorado Conservation Tillage Association Annual Conference Proceedings, pp. 4-5.

Oki, T., Kanae, S., 2006. Global hydrological cycles and world water resources. Science 313, 1068-1072.

Pappas, C., Fatichi, S., Rimkus, S., Burlando, P., Huber, M.O., 2015. The role of local-scale heterogeneities in terrestrial ecosystem modeling. Journal of Geophysical Research: Biogeosciences 120, 341-360.

Peng, C., Apps, M.J., 1999. Modelling the response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes. Ecological Modelling 122, 175-193.

Postel, S.L., 2000. Entering an era of water scarcity: the challenges ahead. Ecological applications 10, 941-948.

Running, S.W., Thornton, P.E., Nemani, R., Glassy, J.M., 2000. Global terrestrial gross and net primary productivity from the earth observing system, Methods in ecosystem science. Springer, pp. 44-57.

Shi, C., Zhan, J., Yuan, Y., Wu, F., Li, Z., 2014. Land Use Zoning for Conserving Ecosystem Services under the Impact of Climate Change: A Case Study in the Middle Reaches of the Heihe River Basin. Advances in Meteorology.

Singh, R., Garg, K.K., Wani, S.P., Tewari, R.K., Dhyani, S.K., 2014. Impact of water management interventions on hydrology and ecosystem services in Garhkundar-Dabar watershed of Bundelkhand region, Central India. Journal of Hydrology 509, 132-149.

Song, W., Deng, X., Liu, B., Li, Z., Jin, G., 2015a. Impacts of Grain-for-Green and Grain-for-Blue Policies on Valued Ecosystem Services in Shandong Province, China. Advances in Meteorology.

Song, W., Deng, X., Yuan, Y., Wang, Z., Li, Z., 2015b. Impacts of land-use change on valued ecosystem service in rapidly urbanized North China Plain. Ecological Modelling.

Song, W., Zhang, Y., 2015. Expansion of agricultural oasis in the Heihe River Basin of China: patterns, reasons and policy implications. Physics and Chemistry of the Earth, Parts A/B/C 89-90, 46-55.

Tian, H., Chen, G., Liu, M., Zhang, C., Sun, G., Lu, C., Xu, X., Ren, W., Pan, S., Chappelka, A., 2010. Model estimates of net primary productivity, evapotranspiration, and water use efficiency in the terrestrial ecosystems of the southern United States during 1895–2007. Forest Ecology and Management 259, 1311-1327.

Tian, Y., Zheng, Y., Wu, B., Wu, X., Liu, J., Zheng, C., 2015. Modeling surface water-groundwater interaction in arid and semi-arid regions with intensive agriculture. Environmental Modelling & Software 63, 170-184.

Veroustraete, F., Sabbe, H., Eerens, H., 2002. Estimation of carbon mass fluxes over Europe using the C-Fix model and Euroflux data. Remote sensing of Environment 83, 376-399.

Verstraeten, W.W., Veroustraete, F., Feyen, J., 2006. On temperature and water limitation of net ecosystem productivity: Implementation in the C-Fix model. Ecological Modelling 199, 4-22.

Wang, G., Chen, J., Wu, F., Li, Z., 2015a. An integrated analysis of agricultural water-use efficiency: A case study in the Heihe River Basin in Northwest China. Physics and Chemistry of the Earth, Parts A/B/C 89-90, 3-9.

Wang, K., 1996. Canopy CO2 exchange of Scots pine and its seasonal variation after four-year exposure to elevated CO2 and temperature. Agricultural and forest meteorology 82, 1-27.

Wang, P., Yu, J., Pozdniakov, S.P., Grinevsky, S.O., Liu, C., 2014. Shallow groundwater dynamics and its driving forces in extremely arid areas: a case study of the lower Heihe River in northwestern China. Hydrological Processes 28, 1539-1553.

Wang, P., Zhang, Y., Yu, J., Fu, G., Ao, F., 2011. Vegetation dynamics induced by groundwater fluctuations in the lower Heihe River Basin, northwestern China. Journal of Plant Ecology 4, 77-90.

Wang, X., Cui, Q., Li, S.Y., 2012. An optimal water allocation model based on water resources security assessment and its application in Zhangjiakou Region, northern China. Resources Conservation and Recycling 69, 57-65.

Wang, Z., Deng, X., Chen, J., 2015b. Impacts of sparing use of water on farmer income of China. Physics and Chemistry of the Earth, Parts A/B/C 89-90, 18-24.

Wang, Z., Deng, X., Li, X., Zhou, Q., Yan, H., 2015c. Impact analysis of government investment on water projects in the arid Gansu Province of China. Physics and Chemistry of the Earth, Parts A/B/C 79-82, 54-66.

Wu, B., Yan, N., Xiong, J., Bastiaanssen, W.G.M., Zhu, W., Stein, A., 2012. Validation of ETWatch using field measurements at diverse landscapes: A case study in Hai Basin of China. Journal of Hydrology 436–437, 67-80.

Wu, F., Deng, X., Yin, F., Yuan, Y., 2013a. Projected changes of grassland productivity along the representative concentration pathways during 2010–2050 in China. Advances in Meteorology 2013.

Wu, F., Zhan, J., Yan, H., Shi, C., Huang, J., 2013b. Land cover mapping based on multisource spatial data mining approach for climate simulation: a case study in the farming-pastoral ecotone of North China. Advances in Meteorology 2013.

Xiao, H., Cheng, G., 2006. Water issue and management at basin level in Heihe River, Northwestern China. Journal of desert research 26, 1-5.

Yan, H., Zhan, J., Jiang, Q.o., Yuan, Y., Li, Z., 2015. Multilevel modeling of NPP change and impacts of water resources in the Lower Heihe River Basin. Physics and Chemistry of the Earth, Parts A/B/C 79-82, 29-39.

Yan, H., Zhan, J., Liu, B., Yuan, Y., 2014. Model estimation of water use efficiency for soil conservation in the Lower Heihe River Basin, Northwest China during 2000–2008. Sustainability 6, 6250-6266.

Ye, Z., Chen, Y., Li, W., 2010. Ecological water demand of natural vegetation in the lower Tarim River. Journal of Geographical Sciences 20, 261-272.

Yin, F., Deng, X., Jin, Q., Yuan, Y., Zhao, C., 2014. The impacts of climate change and human activities on grassland productivity in Qinghai Province, China. Frontiers of Earth Science 8, 93-103.

Zhan, J.Y., Shi, N.N., He, S.J., Lin, Y.Z., 2010. Factors and mechanism driving the land-use conversion in Jiangxi Province. Journal of Geographical Sciences 20, 525-539.

Zhang, F., Feng, Q., Li, X., Wei, Y., 2014a. Remotely-sensed estimation of NPP and its spatial-temporal characteristics in the Heihe River Basin. Journal of Desert Research 34, 1657-1664.

Zhang, L., Li, Y., Zhang, H., Wang, J., 2010. Using a land surface model to simulate Net Primary

Productivity in China comparing with the process model derived by remote sensing, Geoscience and Remote Sensing Symposium (IGARSS), 2010 IEEE International. IEEE, pp. 3291-3294.

Zhang, Y., Song, C., Zhang, K., Cheng, X., Band, L.E., Zhang, Q., 2014b. Effects of land use/land cover and climate changes on terrestrial net primary productivity in the Yangtze River Basin, China, from 2001 to 2010. Journal of Geophysical Research: Biogeosciences 119, 1092-1109.

Zhao, C., Wang, P., Zhang, G., 2015. A comparison of integrated river basin management strategies: A global perspective. Physics and Chemistry of the Earth, Parts A/B/C 89-90, 10-17.

Zhou, Q., Wu, F., Zhang, Q., 2015. Is irrigation water price an effective leverage for water management? An empirical study in the middle reaches of the Heihe River basin. Physics and Chemistry of the Earth, Parts A/B/C 89-90, 25-32.

Zhou, W., Sun, Z.G., Li, J.L., Gang, C.C., Zhang, C.B., 2013. Desertification dynamic and the relative roles of climate change and human activities in desertification in the Heihe River Basin based on NPP. Journal of Arid Land 5, 465-479.

Long time-series NPP and water use efficiency in the Lower Heihe River Basin were estimated.
Spatial patterns of NPP and water use efficiency kept overall unchanged during 2001-2010.
Accumulative water use efficiency first sharply decreased and then increased.
There was still some scope to improve water use efficiency.
Valuable reference information was provided for water resource management and ecological conservation.