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Assessing the impacts of an ecological water diversion project on water consumption through high-resolution estimations of actual evapotranspiration in the downstream regions of the Heihe River Basin, China

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ABSTRACT

Ecological Water Diversion Projects (EWDPs) have been implemented in several endorheic river basins in the arid region of northwest China since the beginning of the new millennium to restore the deteriorated ecosystems. However, the effects of these EWDPs are difficult to evaluate quantitatively. Here, we assessed changes in water use in Ejin Oasis in the downstream region of the Heihe River Basin, which is a typical endorheic river basin in northwest China, based on the estimated evapotranspiration (ET) during the growing season (May to October) in 2000 (before the EWDP) and 2014 (after the EWDP). The ET estimates were based on the modified surface energy balance algorithm for land (M-SEBAL) model and Landsat images. The estimated ET was validated against observations using eddy covariance towers installed on different landscapes in 2014 and was found to have a root mean square error of 1.20 mm day^{-1} and a coefficient of determination of 0.67 at the footprint scale on satellite overpass days. The estimated ETs in two years were also compared with another remote sensing product that showed a similar spatial pattern, with a spatial mean difference of 4 mm and 0.5 mm, respectively. The estimated ET was then used to evaluate the impact of the EWDP on water consumption. The ET over different land use and land cover types increased, with a mean increase of 52% over the 15 years of the implementation of the EWDP in Ejin Oasis. The water consumption in Ejin Oasis in 2014 was approximately twice that in 2000. Among the changes, water consumption by croplands increased significantly, with a maximum increase of 264% because of cropland expansion and increased ET. The increases in water consumption by forests and grasslands were 60% and 25%, respectively. The lake area expanded drastically (from 0 to 37.46 km^2), and the corresponding water consumption caused by evaporation was zero in 2000 and approximately 3.9×10^7 m^3 from May to October in 2014. This work demonstrates that estimates of the ET based on remote sensing can be used as reliable indicators for comprehensive assessments of the impacts of the EWDPs.

1. Introduction

Northwestern China and Central Asia contain the most endorheic river basins in the world. The ecosystems in the downstream areas of these river basins are particularly susceptible to changes in upstream runoff because the precipitation is very low. However, because of increasing water consumption upstream (e.g., increased agricultural irrigation, population expansion and economic development), upstream runoff in many of the area's endorheic river basins has decreased over the past 50 years (Cheng and Li, 2015; Cheng et al., 2014; Glantz, 2005). As a result, the natural ecosystems have degraded, and terminal lakes have receded or even vanished, such as the Aral Sea (Glantz, 2005). Therefore, integrated watershed water resource management is vitally important for sustainable development and the protection of these ecosystems (Cheng et al., 2014).

The Heihe River Basin is one such case. It is the second largest inland river basin in northwestern China and covers an area of approximately 1,432,000 km^2 (Li et al., 2013). This basin is characterized by

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cryosphere conditions (i.e., glaciers, frozen soil, and alpine meadow forest) in its upper reaches, by irrigated croplands in its middle reaches and by riparian ecosystems and deserts in its lower reaches. Because of the large increase in water consumption in the middle reaches of the Heihe River Basin, the discharge from this region decreased sharply between the 1960s and 1990s, which resulted in dried-up terminal lakes, including West Juyan Lake (Gaxun Nuur) and East Juyan Lake (Sogo Nuur) in 1961 and 1992, respectively (Xiao et al., 2016). To avoid ecosystem deterioration in the lower reaches of the Heihe River, the Chinese government has invested a total of 2.3 billion Yuan in the Ecological Water Diversion Project (EWDP) in the Heihe River Basin since 2000 (Guo et al., 2009; Si et al., 2015). Water reached the East Juyan Lake (Sogo Nuur) and West Juyan Lake (Gaxun Nuur) in 2002 and 2003, respectively. After 15 years of integrated water resource managements, the spatiotemporal distribution of water resources has changed dramatically in the lower reaches of the Heihe River, resulting in vegetation recovery and lake restoration (Guo et al., 2009; Hu et al., 2015; Wang et al., 2013; Xiao et al., 2016; Yin et al., 2015). The hydrological cycle of the region and the water allocation and consumption for different land use types have also changed dramatically (Deng et al., 2015).

Evapotranspiration (ET) is the only component of active water consumption in the lower reaches of the Inland River and plays important roles in the water and energy budgets. Moreover, information about the spatial and temporal variability in ET could facilitate quantifying the water consumption and water requirements and, thus, improving the water resource management in these areas. Therefore, this information is also vital for decision-making and evaluation of the EWDP.

Although several studies have analyzed groundwater changes (Guo et al., 2009; Wang et al., 2011a; Wang et al., 2014), vegetation dynamic changes (Wang et al., 2011b), land use and land cover changes (LUCCs; Hu et al., 2015; Nian et al., 2017) and terminal lake restoration (Si et al., 2015; Xiao et al., 2016) after the EWDP and have quantified the actual ET in a specific year (Hochmuth et al., 2015), few studies have focused on ET changes over different land use types since the EWDP was implemented. There are many reasons for this gap. The main reason is the lack of surface observations, especially for ET, which is the most difficult component to measure directly (Senay et al., 2016). Therefore, observations and modeling of ET in the Heihe River represent key focuses of research (Li X. et al., 2009; Li et al., 2013; Li X. et al., 2016; Liu et al., 2016; Ma et al., 2015; Song et al., 2016a; Wang et al., 1993). Mapping regional-scale patterns of ET using remote sensing images has proven to be more promising, economical and efficient than the traditional approaches used to estimate ET, such as weighing lysimeters, the energy balance Bowen ratio (EBBR), eddy covariance (EC) techniques, pan-measurements, sap flow, and scintillometers. Many methods of ET estimation are based on remote sensing, such as the surface energy balance algorithm for land (SEBAL; Bastiaanssen et al., 1998), the modified surface energy balance algorithm for land (M-SEBAL; Long and Singh, 2012), the simplified surface energy balance index (S-SEBI; Roerink et al., 2000), mapping ET at high resolution with internalized calibration (METRIC; Allen et al., 2007), wet METRIC (wMETRIC; Singh and Irmak, 2011), the surface energy balance system (SEBS; Ma et al., 2015; Su, 2002), the operational simplified surface energy balance (SSEBop; Senay et al., 2013), the two-source model (TSM; Norman et al., 1995; Song et al., 2016a; Song et al., 2016b), the atmosphere-land exchange inverse (ALEXI; Anderson et al., 2007), the hybrid dual-source scheme and trapezoid framework-based ET model (HTEM; Yang and Shang, 2013), ETWatch for monitoring regional ET with remote sensing (ETWATCH; Wu et al., 2012) and the actual ET estimation model (ETMonitor; Hu and Jia, 2015). Many papers have reviewed these models (Kustas and Anderson, 2009; Li Z.L. et al., 2009; Liou and Kar, 2014; Wang and Dickinson, 2012). Among these models, the SEBAL model has a strong physical basis, requires few concurrent ground-level observations and has been successfully applied to various ecosystems in more than 30 countries (Bastiaanssen et al., 2005). However, studies (Long and Singh, 2013; Long et al., 2012; Tang et al., 2013) have shown that because end members (hot and cold pixels) are manually identified by operators, the SEBAL model outputs have large uncertainties and that the accuracy is mainly dependent on the operator's experience and the size of the study area (Long and Singh, 2013). Moreover, the end members (hot and cold pixels) are selected by a rectangular framework of the $F_c - T_s$ space, which could distort the spatial distribution of the fluxes (Long and Singh, 2012). Based on the above analysis, Long and Singh (2012) replaced the rectangular framework of the $F_c - T_s$ space in SEBAL with a theoretical trapezoidal framework of F_c and T_s (Sandholt et al., 2002), which reduced the uncertainty in the manually selected end members, the domain dependence and the distortion of the spatial patterns. The M-SEBAL model was validated by the soil moisture atmosphere coupling experiment (SMACEX) sites in central Iowa, U.S. (Long and Singh, 2012) and the Multi-Scale Observation Experiment on Evapotranspiration over heterogeneous land surfaces of The Heihe Watershed Allied Telemetry Experimental Research (HiWATER-MUSOEXE) in the middle reaches of the Heihe River Basin (Zhou et al., 2014). These results indicated that the accuracy of M-SEBAL was generally higher than that of SEBAL and that the spatial patterns of heat flux retrievals from M-SEBAL are closer to observational measurements and represented the heterogeneity of different vegetation covers well (Zhou et al., 2014). Therefore, in this paper, we used the M-SEBAL model to estimate the actual ET during the growing season (May to October) in Ejin Oasis in the downstream region of the Heihe River Basin.

In arid and semi-arid regions, deserts act as landscape matrices, and oases act as landscape mosaics (Cheng et al., 1999; Li et al., 2011). This is especially true in hyperarid environments (e.g., the lower reaches of the Heihe River Basin) where the spatial pattern of the landscape is fragmental. In such fragmental or heterogeneous areas, most pixels in coarse-resolution remote sensing images (e.g., Moderate Resolution Imaging Spectroradiometer [MODIS] and Advanced Very High Resolution Radiometer [AVHRR] images) are mixed, leading to significant challenges in quantifying and validating the ET (water consumption) of different ecosystems. High-resolution images (e.g., Landsat images) have more pure pixels and, thus, produce more accurate ET results at the field scale (Senay et al., 2016).

Therefore, the main objectives of this study were to (1) produce ET (water consumption) estimates during the growing season (May to October) for the downstream region of the Heihe River Basin in 2000 (before the EWDP) and 2014 (after the EWDP); (2) evaluate the performance of Landsat-derived ET estimates using independent datasets, such as EC and other ET products; and (3) evaluate and analyze the effects of the EWDP on the ET values of different land use/land types in Ejin Oasis since 2000 and the driving factors underlying these changes.

This paper is structured as follows. The study area and data are described in Section 2. Section 3 introduces the ET estimation method based on the M-SEBAL model (Sections 3.1 and 3.2) and then presents the validation methods at the footprint scale (Section 3.3) and regional scale (Section 3.4). In Section 4, the Landsat-derived ET estimates are evaluated using independent datasets, such as EC and other ET products and then the change in ET and water consumption (Section 4.3) from 2000 (before the EWDP) to 2014 (after the EWDP) are analyzed. In Section 5, the driving factors underlying the changes between 2000 and 2014 and the representativeness of these changes are discussed. Section 6 presents the main conclusions.

2. Study site and materials

2.1. Study area

The Heihe River Basin is the second largest inland river basin in northwestern China (Fig. 1(a)). The Zhengyi Gorge marks the far boundary of its lower reaches. At the Langxinshan diversion in the Ejin