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Responses of field evapotranspiration to the changes of cropping pattern and groundwater depth in large irrigation district of Yellow River basin

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ABSTRACT

To solve the problems of decreasing water resources from the Yellow River, the renovation project of water-saving and controlling water distribution was implemented in the Hetao Irrigation District of North China since 1999. The local hydrological cycle is expected to be influenced or changed during the past fifteen years through the project. Jiefangzha Irrigation Region, the second large partition of the Hetao Irrigation District, was selected as the typical area to explore the relationship between agricultural water consumption, water distribution, cropping pattern and changing groundwater level. In this paper, the SEBS (Surface Energy Balance System) model and the ESTARFM (Enhanced Spatial and Temporal Adaptive Reflectance Fusion Model) algorithm were applied to produce daily field-scale evapotranspiration (ET) based on Landsat and MODIS data from 2000 to 2015 at intervals. The results indicate that the cropping pattern had changed greatly, while the water table descended through the years. The total agriculture ET stayed relatively stable, with the average annual consumption of 8.9×10^8 m^3. The temporal variation of agriculture ET was not obviously sensitive to the adjustment of cropping pattern. There was no significant difference in April–October ET for different crops, in spite of the clear distinction of ET in each crop-specific growing season. The spatial distribution of agricultural ET did not change in spite of the great adjustment of cropping pattern during fifteen years, which has a close inverse correlation with the groundwater depth. Groundwater depth descended from 1.76 m to 2.33 m during the operation period of the water-saving project, which might reduce the soil evaporation and have a positive effect on soil salinization effectively. Meanwhile, the net irrigation water use efficiency was improved from 0.59 to 0.66. These effects indicate the positive impact of the implemented water-saving renovation project on water management and environment. However, the actual crop coefficient $K_{c,a}$ decreased slightly with the gradually increasing reference evapotranspiration, indicating possible drought stress as an effect of the continuing reduction of the availability of net irrigation water and declining groundwater table.

1. Introduction

Runoff of Yellow River basin has shown a downward trend in recent decades under the situation of climate change and increasing water demand (Fu et al., 2004), which gradually aggravated the gap between supply and demand of water, especially in arid and semiarid regions. Trying to solve the problems, Chinese government launched a water-saving renovation program in large-scale irrigation districts since 1999 and expected to finish in 2020. This program supports implementation of the renovation and reformation of irrigation canal lining and other measures aiming to reduce water distribution from the Yellow River and improve irrigation efficiency in the field (Yang et al., 2012).

Hetao Irrigation District is the third largest irrigation district in China with an average annual precipitation of 130 mm and pan evaporation of 2300 mm. The main crops include spring wheat, spring maize and sunflower planted widely from April to October, irrigated from the Yellow River. The aim of the water-saving ren-

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ovation program and integrated planning is to reduce the use of irrigation water taking directly from the Yellow River, gradually from 5.165 billion m^3 on average before 2000 to 4 billion m^3 in 2015. This has led to the lowering of groundwater levels and significant changes in the regional water cycle (Xu et al., 2010; Yang et al., 2012).

Evapotranspiration (ET), as the basis of water management, is the major component of energy and water balance in agricultural systems (Burba and Verma, 2005). The temporal and spatial characteristics of actual ET is vital for studying the climate changes, agricultural hydrological cycle and irrigation scheduling (Gowda et al., 2008; Lei and Yang, 2010). The improving remote sensing technology makes it possible to acquire regional land surface characteristics and model the surface energy fluxes in large scale. Over the last decades, several models have been developed to evaluate regional ET based on land surface energy balance, such as Surface Energy Balance Index (SEBI) (Menenti and Choudhury, 1993), Two-Source Energy Balance Model (TSEB) (Norman et al., 1995), Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a), Simplified Surface Energy Balance Index (S-SEBI) (Roerink et al., 2000), Surface Energy Balance System (SEBS) (Su, 2002) and Mapping ET with Internalized Calibration (METRIC) (Allen et al., 2007), and so on. These models were generally in accordance with results based on measurements in the field. Overall, the SEBS model is the easiest to apply because of the easily obtained input data. In this study, it was selected to estimate the local field evapotranspiration, considering its good performance in the North China plain, with the relative error of the latent heat flux within 20% in both wheat and maize growing seasons (Yang et al., 2010).

Under the limitation of remote sensing technology and costs, it is difficult for satellite system to capture the surface changes at very high spatial resolution with frequent coverage (Zhu et al., 2010). However, some satellite data have been proved to be efficient for mapping biophysical vegetation parameters with a spatial resolution from 6 to 30 m, such as IRS, SPOT, CBERS and Landsat. However, the long revisit cycle and often occurring cloud contamination restrain their applications in monitoring the rapid changes of the vegetation parameters and surface energy fluxes in the growing season (Timmermans et al., 2007; Wulder et al., 2008; Choi et al., 2009; Aanderson et al., 2012; Sertel and Akay, 2015). The relative coarse resolution sensors, such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Very High Resolution Radiometer (AVHRR), can provide more frequent observations but hardly quantify the ecosystem process within complex underlying surfaces (Pouliot et al., 2009; Yang et al., 2010; Yang et al., 2012; Kiptala et al., 2013; Mukherjee et al., 2014). To take advantage of remote sensing data from both finer and coarser resolution sensors, data fusion approaches offer a feasible and cheap way to integrate the best quality of multiple remote sensing data to reconstruct high spatiotemporal land surface dynamics (Gao et al., 2006; Hilker et al., 2009a; Zhu et al., 2010; Bhandari et al., 2012).

Some traditional fusion techniques, such as the intensity-hue-saturation (Carper et al., 1990), component substitution (Shettigara, 1992) and wavelet decomposition (Yocky, 1996), were employed to enhance the spatial resolution by integrating high-resolution panchromatic data and coarse-resolution multispectral bands. However, these methods are not suitable to improve the temporal coverage in capturing the rapid surface changes, especially for croplands. In order to enhance the resolution at both spatial and temporal scale, Gao et al. (2006) proposed the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) to restructure daily Landsat-scale reflectance combining daily MODIS data with 16-days Landsat images. Roy et al. (2008) developed a semi-physical fusion approach to solve the limitation of directional dependence of reflectance as a function of the sun-target-sensor geometry, and used the MOIDS BRDF/Albedo land surface products and Landsat ETM + data to predict ETM + reflectance. Furthermore, Hilker et al. (2009a) used Spatial Temporal Adaptive Algorithm for mapping Reflectance Change (STAARCH) to solve the transient disturbance on the STARFM and improve the accuracy of synthetic Landsat images for the vegetated land surface. Nevertheless, these improved methods usually rely on the homogeneity of the underlying surface and have the same difficulty in predicting the reflectance of heterogeneous landscapes with complex vegetation types, soil water and meteorological conditions. Therefore, the Enhanced Spatial and Temporal Adaptive Reflectance Fusion Model (ESTARFM) was proposed by Zhu et al. (2010). The most significant improvement of ESTARFM is to use the conversion coefficient to enhance the accuracy of prediction for heterogeneous landscapes, which deals with the spatial information more effectively (Zhu et al., 2010).

Data fusion approaches were usually applied for reconstructing the low-level product (e.g., spectral reflectance and vegetation indices) with little variation over multiday intervals (Gao et al., 2006; Hilker et al., 2009a,b; Zhu et al., 2010). Because of the rapid change of land surface parameters with time, it is difficult to blend in the thermal data to produce the Land Surface Temperature (LST) datasets and estimate the latent heat flux. In addition, the LST depends heavily on the view angle of sensors, which makes it more complicated to integrate the multi-sensor images. Thus, Cammalleri et al. (2013) integrated the MOIDS-ET (1 km, daily) and Landsat-ET (30 m, 16-day) directly to produce daily field-scale ET using STARFM and successfully achieve the data fusion between higher-order products. Then the algorithm was used to map daily evapotranspiration at field scale over rainfed and irrigated agricultural areas with the root mean square error varying from 1.11 mm day^{-1} to 1.81 mm day^{-1}, respectively (Cammalleri et al., 2014).

In this study, the SEBS model and ESTARFM methodology were chosen to reconstruct daily field-scale ET maps during the whole growing season in seven different years in the period from 2000 to 2015. The main activities were: (1) to reconstruct the daily field-scale ET using Landsat-ET and MODIS-ET datasets and evaluate the performance of the ESATRFM; (2) to analyze the seasonal and inter-annual variation of ET for different crops and the controlling factors on ET in the study area; (3) to analyze the temporal and spatial characteristics of agriculture ET and its response to cropping pattern and groundwater depth; and (4) to evaluate the impacts of the water-saving renovation project.

2. Materials and methods

2.1. Study area

The Jiefangzha irrigation region was selected as the research area, situated in the western part of the Hetao Irrigation District (N40°34′–41°14′, E106°43′–107°27′). The altitude in the southwest area is higher than in northeast area which varies from 1030 m to 1046 m above sea level. Fig. 1 shows the location in detail. The average temperature in this area is 9 °C with mean annual precipitation of 151.3 mm and pan evaporation of 2300 mm. The soil texture is mostly silty clay loam with severe salinization. The water table is raised as results of excessive irrigation and local deficient drainage system, which severely induces the problem of secondary salinization directly (Yu et al., 2010; Xu et al., 2010).

The total area of the Jiefangzha irrigation region is about 2345 km^2, with the agriculture land making up 60% of it. The main crops in the study area include spring wheat (from late March to late July), spring maize (from late April to mid-October), sunflower (late May to mid-October) and interplanting crops (late March to mid-October, mainly for wheat and sunflower), whose layout depend