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Estimation of daily evapotranspiration and irrigation water efficiency at a Landsat-like scale for an arid irrigation area using multi-source remote sensing data

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ABSTRACT

The estimation of land-surface evapotranspiration (ET) at high spatial and temporal resolutions is important for management and planning of agricultural water resources, but available remote sensing data generally have either high spatial resolution or high temporal resolution. To overcome this limitation, we evaluated the use of a data fusion scheme, Enhanced Spatial and Temporal Adaptive Reflectance Fusion Model (ESTARFM), to determine the surface parameters needed to estimate daily ET at a Landsat-like scale (100 m). In particular, we fused Moderate Resolution Imaging Spectroradiometer (MODIS) data with Landsat Enhanced Thematic Mapper Plus (ETM+) data in analysis of the Heihe River Basin (HRB), an arid region of Northwest China. The surface parameters were then used to drive the revised Surface Energy Balance System (SEBS) model to estimate daily ET at a spatial resolution of 100 m for this an arid irrigation area during the crop growth period (April to October) in 2012. The results showed that the daily ET estimates had a mean absolute percent error (MAPE) of 12% and a root mean square error (RMSE) of 0.81 mm/day relative to ground measurements from 18 eddy covariance (EC) sites in the study area. The validation results indicated good accuracy for land cover types of maize and vegetables, a slight overestimation for residential and wetland sites, and a slight underestimation for orchard site. Our comparison of the input parameter fusion approach (IPFA) and the ET fusion approach (ETFA) with field measurements indicated the IPFA was superior than the ETFA for land surfaces with high spatial heterogeneity. Furthermore, our high spatiotemporal ET estimates indicated that irrigation water efficiencies of the irrigation districts (mean: 70%) and villages (mean: 62%) had large spatial heterogeneity. These results point to the need for calculating ET at a high spatiotemporal resolution for monitoring and improving irrigation water efficiency at local scales. Our findings suggest that the proposed framework of estimating daily ET at a Landsat-like scale using multi-source data may also be applicable to other heterogeneous landscapes by providing a foundation for management of water resources at the basin or finer scales.

1. Introduction

Irrigation accounts for approximately 70% of the world's total freshwater withdrawals (WWAP, 2016). Agricultural production in arid and semi-arid areas usually requires irrigation, and these regions consume approximately 80% to 95% of the total freshwater used for irrigated agriculture in Western Europe (Battude et al., 2017), Western Asia (Elnesr and Alazba, 2013), and Northwest China (Chen et al., 2003). Irrigation water efficiency is a measure of the effectiveness of irrigation that researchers commonly use to characterize farm lands (Ahadi et al., 2013). As fresh water has become increasingly scarce in many regions of the world, it is important to improve the efficiency of irrigation. Additionally, quantifying current irrigation water efficiency can provide a basis for improving efficiency and the management of water resources.

Quantification of irrigation water efficiency at the field scale first requires accurate and high spatiotemporal resolution estimates of surface evapotranspiration (ET) (Bastiaanssen et al., 2005; Anderson et al., 2007; Allen et al., 2008; Yang et al., 2012; Anderson et al., 2012a,b; Cammalleri et al., 2008, 2013; Wu et al., 2015; Zayed et al., 2016;

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Senay et al., 2016; Bai et al., 2017), and these measurements can provide a basis for making decisions regarding irrigation management (Fereres and Soriano, 2007; Fraiture and Wichelns, 2010; Martin et al., 2013). Satellite sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), the Advanced Very High Resolution Radiometer (AVHRR), and the Visible Infrared Imaging Radiometer (VIIRS) provide daily thermal infrared (TIR) data, but their resolutions (~1 km) are too coarse for estimation of ET at the field scale (Bastiaanssen et al., 2001; Allen et al., 2008; Cammalleri et al., 2013, 2014a,b; Wu et al., 2015). On the other hand, the Landsat 5 Thematic Mapper (TM)/7 Enhanced Thematic Mapper Plus (ETM+)/8 Thermal Infrared Sensor (TIRS) and the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) provide high spatial resolution thermal infrared (TIR) data (approximately 100 m), but they have a lengthy return interval, and cloud cover can interfere with image acquisition. Therefore, a method that combines the fine spatial resolution of Landsat-like data and the high temporal resolution of MODIS-like data will provide significant benefits for water resource management at the field scale (Cammalleri et al., 2013, 2014a,b). Previous studies have proposed several methods to overcome the limitations of these imaging methods for estimation of regional ET at high spatiotemporal resolutions: Thermal sharpening (Kustas et al., 2003; Bindhu et al., 2013; Agam et al., 2007, 2008), simple output disaggregation models (Hong et al., 2011; Eswar et al., 2013, 2017), and data fusion (Cammalleri et al., 2013, 2014a,b; Bai et al., 2017).

In general, two strategies can perform data fusion to estimate ET at high spatiotemporal resolution using data fusion method. One method is the ET fusion approach (ETFA), in which MODIS- and Landsat-derived ET maps are fused to compensate for their spatial and temporal resolutions, respectively. Previous studies have used the ETFA to estimate daily ET in fields of rain-fed and irrigated corn, soybean, and cotton (Cammalleri et al., 2013, 2014a,b), and irrigated vineyards (Semmens et al., 2016). Additionally, Bai et al. (2017) integrated MODIS ET (250 m, daily) and Landsat ET to produce daily field-scale ET data in the western part of the Hetao Irrigation District of North China. Another method is the input parameter fusion approach (IPFA). This method fuses spectral reflectance and radiance observations from multiple satellite sensors to derive the physical parameters of the land surface (albedo, emissivity, land surface temperature [LST], and vegetation coverage), and then uses these parameters as inputs for ET models.

Previous studies have successfully applied two data fusion algorithms for ETFA: The Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) (Gao et al., 2006; Cammalleri et al., 2013, 2014a,b) and the enhanced STARFM (ESTARFM) (Zhu et al., 2010; Bai et al., 2017). Both algorithms identify spatial variations from high spatial resolution images and examine temporal changes from high temporal resolution images to produce new simulated images (Gao et al., 2006, 2017; Zhu et al., 2010). Emelyanova et al. (2013) proposed a framework for selection of blending algorithms based on partitioning of the spatial and temporal variances and suggested that ESTARFM was a superior blending algorithm when the spatial variance in the relevant spectral bands was predominant. Jarihani et al. (2014) found that STARFM had better accuracy when the temporal variance was higher than the spatial variance ($\sigma_T^2/\sigma_S^2 > 1$), but ESTARFM had typically had better accuracy when the spatial variance was higher ($\sigma_T^2/\sigma_S^2 < 1$).

Over the last two decades, many studies have used the surface energy balance method to estimate ET for irrigated agricultural areas worldwide (Bastiaanssen et al., 2001; Allen et al., 2005; Droogers et al., 2010; Liou and Kar, 2014; Senay et al., 2016; Bai et al., 2017). The Surface Energy Balance System (SEBS) model (Su, 2002) is one of the most widely used one-source energy balance models. This model uses a sequence of physically-based equations (Su et al., 2001; Su, 2002) to estimate ET rates at local and regional scales (Jia et al., 2003; Su et al., 2005; Chen et al., 2014). However, the SEBS model may underestimate the sensible heat flux (McCabe and Wood, 2006; Choi et al., 2009; Timmermans et al., 2013; Chirouze et al., 2014; Ma et al., 2015). Moreover, previous studies have reported uncertainties of the SEBS model, and the need for modifications when it is implemented at local and regional scales (Gokmen et al., 2012; Chen et al., 2013a,b). For example, to improve ET estimates over heterogeneous oasis-desert surfaces in the midstream of the Heihe River Basin (HRB) of Northwest China, Ma et al. (2015) used ground measurements to modify several key parameters of the SEBS model by using ground measurements. Clearly, given the possible sensitivity of the model outputs to the "model physics" and parameterization schemes, calibration of the model using ground observations improves its performance at the scale of the observations (Liu et al., 2007a,b; Liu et al., 2013, 2014, 2015; Yang et al., 2008; Chen et al., 2013a; Mallick et al., 2014, 2015, 2016; Wang et al., 2018).

The Heihe River Basin (HRB) is one of the most hydrologically vulnerable areas worldwide, and is typical of many arid and semi-arid regions (Cheng et al., 2014). Recently, water scarcity and conflicts among users have become more intense in the HRB due to the increasing use of irrigation water by the midstream regions and the environmental flow requirements of the downstream regions (Cheng et al., 2014). As a first step toward resolving these conflicts for the HRB, it is necessary to examine irrigation water efficiency at high spatiotemporal resolution in this region (Li et al., 2018). In addition, an analysis of the rich experimental data in the HRB (Li et al., 2013, 2018) will allow this area to serve as a testbed for additional examinations of water-related issues in other arid and semi-arid regions.

ET is a required input for calculation of irrigation water efficiency. Thus, estimations of ET at a high spatiotemporal resolution are needed to determine irrigation water efficiency at high spatiotemporal resolution. We produced daily Landsat-like scale ET data for the HRB area by deploying the SEBS model and fusing multiple sources of satellite remote sensing data with ground measurements in the HRB. This work is a necessary first step toward resolving water conflicts in the HRB area. Our specific objectives were to: (i) estimate and validate daily ET at a Landsat-like scale for the midstream irrigated area of the HRB using a multi-source remote sensing data fusion method (ESTARFM) with the revised SEBS model; (ii) analyze the spatiotemporal variations in the ET estimates; and (iii) assess the irrigation water efficiency for the different irrigation districts and villages using the ET estimates. The research framework employed here could be applicable to other arid and semi-arid regions, and our specific findings could also provide a basis for water resource management practices in these other regions.

2. Experiments and data

2.1. Study area and HiWATER-MUSOEXE experiments

The HRB covers an area of approximately 143,000 km^2 in the arid region of Northwest China (Fig. 1, left). It is the second largest inland river basin in China and has various types of land cover. The HRB is dry and has strong winds, high solar radiation, and large daily temperature variations. The annual average stream flow measured at the Yingluo gauge (outlet from upstream) was 15.97 × 10^8 m^3 from 1945 to 2012. In the midstream of the HRB, the main crop is maize, and the limited water resources are mainly used by the irrigated oasis, which covers approximately 12% of the entire HRB. This area has become an important source of commodity grains in Northwest China. Irrigation water in the HRB is primarily from the surface water of the main stream of the Heihe River, and there are supplemental withdrawals from groundwater sources.

The study area (90 km × 90 km) is in the midstream of the HRB. This area covers 12 irrigation districts (Fig. 1, right; Shangsan, Daman and Yingke, Ganjun, Xigan, Shahe, Wujiang, Yanuan, Banqiao, Pingchuan, Liaoquan, and Liyuan River) and has > 4000 pumping wells. The soil is mainly loam in the irrigation districts, and is mixed loam and sand in the barren desert.