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Satellite-based water use dynamics using historical Landsat data (1984–2014) in the southwestern United States

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ABSTRACT

Remote sensing-based field-scale evapotranspiration (ET) maps are useful for characterizing water use patterns and assessing crop performance. The relative impact of climate variability and water management decisions are better studied and quantified using historical data that are derived using a set of consistent datasets and methodology. Historical (1984–2014) Landsat-based ET maps were generated for major irrigation districts in California, i.e., Palo Verde and eight other sub-basins in parts of the middle and lower Central Valley. A total of 3396 Landsat images were processed using the Operational Simplified Surface Energy Balance (SSEBop) model that integrates weather and remotely sensed images to estimate monthly and annual ET within the study sites over the 31 years. Model output evaluation and validation using gridded-flux data and water balance ET approaches indicated relatively good correspondence (R^2 up to 0.88, root mean square error as low as 14 mm/month) between SSEBop ET and validation datasets. In a pairwise comparison, annual variability of agro-hydrologic parameters of actual evapotranspiration (ET_a), land surface temperature (T_s), and runoff (Q) were found to be more variable than their corresponding climatic counterparts of atmospheric water demand (ET_o), air temperature (T_a), and precipitation (P), revealing process differences between regional climatic drivers and localized agro-hydrologic responses. However, only T_a showed a consistent increase (up to 1.2 K) over study sites during the 31 years, whereas other climate variables such as ET_o and P showed a generally neutral trend. This study demonstrates a useful application of “Big Data” science where large volumes of historical Landsat and weather datasets were used to quantify and understand the relative importance of water management and climate variability in crop water use dynamics in regards to the linkages among water management decisions, hydrologic processes and economic transactions. Irrigation district-wide ET_a estimates were used to compute historical crop water use volumes and monetary equivalents of water savings for the Palo Verde Irrigation District (PVID). During the peak crop fallowing year in PVID, the water saved reached a maximum of ~107,200 acre-feet in 2011 with an estimated monetary payout value of $20.5 million. A significant decreasing trend in actual ET despite an increasing atmospheric demand in PVID highlights the role of management decisions in affecting local hydrologic processes. This study has importance for planning water resource allocation, managing water rights, sustaining agricultural production, and quantifying impacts of climate and land use/land cover changes on water resources. With increased computational efficiency, similar studies can be conducted in other parts of the world to help policy and decision makers understand and quantify various aspects of water resources management.

1. Introduction

Estimates of historical water use, particularly from agricultural fields, are crucial for planning water resource allocation, managing water rights, sustaining agricultural production, and quantifying the impacts of climate change and land use/land cover changes on water resources over space and time.

Local and regional hydrologic processes are impacted by the water lost during evapotranspiration (ET) due to soil-plant-atmosphere interactions. The effect of ET on hydrology and climate particularly in arid/semi-arid areas with intensive agriculture, such as the Central Valley in California, shows wide ranging impacts (Felton 1979; Jin et al. 2012; Lo and Famiglietti 2013; Lobell et al. 2009; Shelton 1987; Sorooshian et al. 2014). Modeling results have shown that irrigation-induced ET exhibits a long-term decreasing trend in the western United

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States (Sorooshian et al. 2014). Based on studies in several major irrigated regions of the world, Lobell et al. (2009) found substantial regional differences in the magnitude of irrigation-induced cooling depending upon differences in extent of the irrigated area, differences in the simulated soil moisture for the control simulation (without irrigation), and the nature of cloud response to irrigation.

Remotely sensed images are widely used to quantify daily and seasonal ET estimates over large areas in river basins (Anderson et al. 2011; Bastiaanssen et al. 2014; Senay et al. 2016; Singh et al. 2014). Thermal infrared (TIR) sensors available on Landsat, Moderate Resolution Imaging Spectroradiometer (MODIS), and other satellites are vital to capturing variations of land surface temperature (T_s). T_s provides valuable information about the surface and subsurface moisture status required for estimating ET and detecting the onset and severity of drought (Anderson et al. 2011). Since 1972, the Landsat series of satellites has been collecting global images and the Landsat archive is the world's longest continuously acquired collection of remotely sensed data. With the launch of Landsat 4 in 1982, Landsat TIR images have enabled scientists and modelers to use energy balance models to estimate ET using spatially explicit T_s derived from the thermal band.

The rich archive of moderately high-resolution Landsat imagery combined with a simplified energy balance model can reliably quantify evapotranspiration in irrigated fields (Senay et al. 2013; Senay et al. 2016; Singh et al. 2014; Velpuri et al. 2013). This approach is not only suitable for scientific investigations of hydrologic processes, but also provides an advantageous and efficient tool for water management agencies and farmers to make decisions about water budgeting and irrigation scheduling. Researchers have used Landsat time series for understanding the surface water extent dynamics at the subcontinental scale (Mueller et al. 2016; Tulbure et al. 2016). The time is ripe for "Big Data" remote sensing – the analysis of millions of freely available Landsat images – to understand historical crop water use dynamics and the links between water resources and land management decisions.

The U.S. Geological Survey (USGS) has played a critical role in utilizing and promoting remote sensing data in water resource management. In 1981, the USGS established an experimental project to assess the possible and practical use of remote sensing to estimate ET as an approximation of consumptive use of water in the lower Colorado River Basin (Raymond and Rezin 1989). In recent years, the USGS started using remotely sensed images in implementing the national water availability and use assessment program (Alley et al. 2013; Michelsen et al. 2016). The approach for estimating ET using remote sensing data has evolved from a simple crop coefficient-based method (Raymond and Rezin 1989) to an energy balance-based method using the latest Landsat 8 data (Senay et al. 2016). Remotely sensed images have been used in two well-documented irrigated regions in the United States, specifically the Palo Verde Irrigation District (PVID) (Chatterjee et al. 2012; Elhaddad et al. 2011; Raymond and Rezin 1989) and the Central Valley (Anderson et al. 2012; Fisher et al. 2007; Marshall et al. 2016; Semmens et al. 2015) in California. One of the main advantages of this ET time series is the higher spatial resolution of Landsat imagery and the relatively long record. These studies (and many more) have provided valuable information on hydrologic regimes within the study site using satellite data, but to our knowledge, no study has been carried out to estimate the historical ET (>30 years) across these regions using a consistent approach based on remote sensing data.

The main objective of this study is to quantify and characterize the spatio-temporal dynamics of historical (1984–2014) ET using Landsat for the Palo Verde Irrigation District along the lower Colorado River, and for irrigation districts in California's Central Valley. Furthermore, seven agro-climatic/hydrologic variables were evaluated for their spatio-temporal dynamics. Climatic variables refer to those that are mainly a result of large-scale interactions between solar radiation and the atmosphere such as atmospheric demand (ET_o), daily maximum air temperature (T_a) and precipitation (P). On the other hand, agro-hydrologic variables refer to those parameters that are mainly influenced by land surface processes such as soil moisture and vegetation conditions and operate at a local scale: actual ET (ET_a), land surface temperature (T_s), runoff (Q) and Normalized Difference Vegetation Index (NDVI).

2. Methodology

2.1. Study sites

2.1.1. Palo Verde Irrigation District

The Palo Verde Irrigation District (PVID) has an area of about 490 km^2 in Riverside and Imperial Counties (California) and La Paz County (Arizona) and is located along the Colorado River bordering California and Arizona (Fig. 1). We chose to use hydrological unit codes (HUC) at the HUC8 level to delineate sub-basin areas from watershed boundaries (https://water.usgs.gov/GIS/huc.html). In this study, the PVID boundary we used is the subset of the Imperial Reservoir HUC8 boundary. The predominant soil within the PVID is sandy loam, and mean annual precipitation is <100 mm. Hot, long growing seasons, mild winters, and a water supply from the Colorado River allow for multiple crops to be grown and harvested throughout the year. Alfalfa is the most dominant crop grown within the PVID among other crops such as cotton, wheat, barley, maize, vegetables, melons, and citrus. Detailed records of water supply and consumptive use in the lower Colorado River Basin are provided by the U.S. Bureau of Reclamation (http://www.usbr.gov/lc/region/g4000/wtracct.html, accessed on 22 Feb, 2016).

2.1.2. Central Valley

The middle to southern portion of the Central Valley in California, between the Sierra Nevada Mountains and the Coast Ranges, is one of the most productive agricultural areas in the United States (Fig. 1). Average annual precipitation ranges from about 400 mm in the northwestern part of the valley to <100 mm in the southeast. The Central Valley climate is characterized by hot, dry summers and mild, rainy winters. Snowpack on the Sierra Nevada is a major source for the supply of water within the valley. As the largest single agricultural area in California, this region leads in almost all categories of agricultural production — total acreage, cultivated acreage, irrigated acreage, water use, and value of production. Crops grown in the valley include grapes, cotton, almonds, citrus, alfalfa, and a diverse range of vegetables. In this study, we chose eight HUC8 sub-basins (Fig. 1) classified into two groups as Middle Central Valley (Rock Creek, Lower San Joaquin, Middle San Joaquin and, Fresno River) and Lower Central Valley (Upper Kaweah, Upper Tule, Upper Deer and, Upper Poso) sub-basins.

2.2. Input datasets

This study focused on the use of Landsat 5, Landsat 7, and Landsat 8, which all share the same global orbit (U.S. Geological Survey, 2015). We downloaded 3396 total Landsat images including 1776 images covering the PVID (Paths 38–39, Row 37) and 1620 images covering the Middle and Lower Central Valley sub-basins in southern California (Path/Row 42/35, 43/34).

Table 1 shows the number of Landsat images processed for each of the 4 path/rows. About 58% of images were from Landsat 5, 38% from Landsat 7, and 4% from Landsat 8. The number of images used per year ranged from a minimum of 6 (1984) with one satellite in orbit to a maximum of 45 (2004) when using two satellites together. The time interval between used images also varied depending on cloud cover and the number of satellites in the orbit. In general, there is an 8-day repeat cycle during years with two satellites (1999–2011; 2013–2014) and increasing to a 16-day repeat cycle during years with only one satellite (1984–1998; 2012).

The thermal band (Band 6 in Landsat 5/7 and Band 10 in Landsat 8) was used to compute T_s and the NDVI was computed from top-of-atmosphere reflectance in red and near-infrared bands. We used the Fmask

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