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Evaluating Landsat 8 evapotranspiration for water use mapping in the Colorado River Basin

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ABSTRACT

Evapotranspiration (ET) mapping at the Landsat spatial resolution (100 m) is essential to fully understand water use and water availability at the field scale. Water use estimates in the Colorado River Basin (CRB), which has diverse ecosystems and complex hydro-climatic regions, will be helpful to water planners and managers. Availability of Landsat 8 images, starting in 2013, provides the opportunity to map ET in the CRB to assess spatial distribution and patterns of water use. The Operational Simplified Surface Energy Balance (SSEBop) model was used with 528 Landsat 8 images to create seamless monthly and annual ET estimates at the inherent 100 m thermal band resolution. Annual ET values were summarized by land use/land cover classes. Croplands were the largest consumer of "blue" water while shrublands consumed the most "green" water. Validation using eddy covariance (EC) flux towers and water balance approaches showed good accuracy levels with R^2 ranging from 0.74 to 0.95 and the Nash–Sutcliffe model efficiency coefficient ranging from 0.66 to 0.91. The root mean square error (and percent bias) ranged from 0.48 mm (13%) to 0.60 mm (22%) for daily (days of satellite overpass) ET and from 7.75 mm (2%) to 13.04 mm (35%) for monthly ET. The spatial and temporal distribution of ET indicates the utility of Landsat 8 for providing important information about ET dynamics across the landscape. Annual crop water use was estimated for five selected irrigation districts in the Lower CRB where annual ET per district ranged between 681 mm to 772 mm. Annual ET by crop type over the Maricopa Stanfield irrigation district ranged from a low of 384 mm for durum wheat to a high of 990 mm for alfalfa fields. A rainfall analysis over the five districts suggested that, on average, 69% of the annual ET was met by irrigation. Although the enhanced cloud-masking capability of Landsat 8 based on the cirrus band and utilization of the Fmask algorithm improved the removal of contaminated pixels, the ability to reliably estimate ET over clouded areas remains an important challenge. Overall, the performance of Landsat 8 based ET compared to available EC datasets and water balance estimates for a complex basin such as the CRB demonstrates the potential of using Landsat 8 for annual water use estimation at a national scale. Future efforts will focus on (a) use of consistent methodology across years, (b) integration of multiple sensors to maximize images used, and (c) employing cloud-computing platforms for large scale processing capabilities.

1. Introduction

Water management principles and techniques are required to optimize the beneficial uses of the available water resources to meet human and ecological needs. Critical elements of water management include knowledge of supply and demand along with the spatiotemporal dynamics of the sources (e.g., reservoirs, streams, wells) and uses (e.g., irrigation, power generation, and domestic supply). Since 1950, the U.S. Geological Survey (USGS) has published national estimates of water use at 5-year intervals using varied data sources such as pumping, crop coefficients, and withdrawals, with all having different levels of accuracy (Holland, 1992; Solley, Merk, & Pierce, 1988). In 1977, the USGS National Water-Use Information Program (NWUIP) was established to produce more uniformly acquired water use data using guidelines and standards to meet regional and national needs from data aggregated at the county level (Mann, Moore, & Chase, 1982).

Although NWUIP improved the quality of water use information by standardizing the terminology, definition, and categories of water use (irrigation, power generation, domestic, etc.) that are adopted by the water use collecting agencies (federal, state, and local), NWUIP faced

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several challenges in obtaining accurate and timely information, partly attributable to the varying methods of water use estimation used for each category by different states and agencies (Maupin et al., 2014). For example, since 2000, NWUIP discontinued the estimation and reporting of return flow (the portion of water returning to the source after a point of application) and consumptive use (the fraction of water removed from subsequent availability due to evapotranspiration or incorporation into products) due to data constraints (Maupin et al., 2014).

According to the most recent nationwide 5-year water use compilation (based on withdrawal information), 2010 had the lowest annual consumptive use in the United States since 1970 (Maupin et al., 2014). With a total water withdrawal of 491 billion m^3/year (bm^3/year) or 355 billion gallons per day (bgal/d), 2010 water withdrawal was 13% lower than that during 2005, with 86% and 14% split between freshwater and saline-water sources, respectively. The two largest water users remained thermoelectric and irrigation in 2010. Withdrawal for thermoelectricity accounted for 45% of total water withdrawals (fresh and saline sources), with 38% of the total withdrawal from freshwater sources.

On the other hand, irrigation (all freshwater, a total of 159 bm^3/year or 115 bgal/d) accounted for 38% of total withdrawal for all uses, or 61% of total water use excluding thermoelectric, and represented the lowest total irrigation water withdrawal since 1965 (Maupin et al., 2014).

To place the 2010 total withdrawal in perspective, the 491 bm^3/year withdrawal is equivalent to 24.6 times the mean (1906–2012) annual flow (natural) of the Colorado River (19.94 bm^3/year or 16.16 ac-ft, (USBR, 2015) at a point above the Imperial Dam (USGS stream gage number 09429490) located at the border of California and Arizona. Although the natural flow of the river reaches close to 20 bm^3/year, the actual annual flow volume leaving the border to Mexico is small with the minimum set at 1.85 bm^3/year (1.5 million ac-ft) (USBR, 2015). The balance is allocated and used to meet various water use demands, from irrigation in the basin to industrial use and domestic water supply in the major cities of the Southwest.

One of the challenges of estimating actual water use by irrigation using withdrawal data is that different crops use water at different rates in a given location, and the same crop uses water differently in a different climatic setting within the same basin. Furthermore, irrigation efficiencies related to the conveyance type (lined versus unlined canals) and application methods (surface versus sprinkler) bring large disparities in estimating crop consumptive use using total withdrawal amounts.

The USGS National Water Census research program is focused on developing new tools to quantify and map evapotranspiration (ET) for two major purposes: (1) estimating crop water use at a county level to support the NWUIP's requirements, and (2) estimating basin-scale water availability (relative proportion of the different water balance components in a watershed) at the hydrologic unit code (HUC) 12 level for the entire nation. Although daily estimates of ET are desired for both objectives, the initial goal is to produce seasonal ET estimates for the previous year by April of a given year. Thus, knowledge of irrigation water use of the previous year can be used for assessing water use needs for the upcoming crop growing season (May to September). The USGS National Water Census is implemented as part of the Department of Interior's WaterSMART (Sustain and Manage America's Resources for Tomorrow) initiative on water use and availability (DOI, 2011).

Remote sensing approaches for estimating evapotranspiration are gaining prominence for their large area coverage using a consistent dataset and the capability to map the spatial variability of ET at subfield scales. Evapotranspiration is an important process in the hydrologic cycle. Among the major water budget components, ET is in a gaseous state as opposed to precipitation and streamflow, making it the most difficult component to measure directly. ET comprises two sub-processes: (1) evaporation from the soil and vegetation surfaces and (2) transpiration from the plants. Consequently, ET plays a major role in the exchange of mass and energy between the soil-water-vegetation system and the atmosphere. Knowledge of the rate and amount of ET for a given location is an essential component in the design, development, and monitoring of hydrologic, agricultural, and environmental systems.

Several methods for remotely sensed ET of irrigated fields located under uniform hydro-climatic regions have been shown to be reliable. These methods include the Surface Energy Balance Index (SEBI) (Menenti & Choudhury, 1993), Two Source Model (TSM) (Norman, Kustas, & Humes, 1995), Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen, Menenti, Feddes, & Holtslag, 1998), Simplified Surface Energy Balance Index (S-SEBI) (Roerink, Su, & Menenti, 2000), Surface Energy Balance System (SEBS) (Su, 2002), ET Mapping Algorithm (ETMA) (Loheide & Gorelick, 2005), Atmosphere-Land Exchange Inverse (ALEXI) (Anderson, Norman, Mecikalski, Otkin, & Kustas, 2007), Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) (Allen, Tasumi, & Trezza, 2007), Simplified Surface Energy Balance (SSEB) (Senay, Budde, Verdin, & Melesse, 2007) and wet METRIC (wMETRIC) (Singh & Irmak, 2011). Reviews of these and other methods for estimating ET using remotely sensed data are presented by other researchers (Allen, Pereira, Howell, & Jensen, 2011; Glenn, Neale, Hunsaker, & Nagler, 2011; Gowda et al., 2007; Kalma, McVicar, & McCabe, 2008). The choice of ET model and input data is likely to have a bearing on model performance at geographical scales of analysis (Fisher, Whittaker, & Malhi, 2011).

Evapotranspiration mapping across complex hydro-climatic conditions proves challenging due to the difficulty of solving the energy balance equations and the required model parameters because of increased uncertainty with input data and model structures, particularly across scene boundaries. Thus, to meet the needs of a basin-wide estimate, Senay et al. (2013) introduced a novel empirical parameterization to an existing simplified modeling approach (Senay et al., 2007) to produce a seamless ET across image-scenes using the Operational Simplified Surface Energy Balance (SSEBop) approach. A comprehensive validation of SSEBop ET estimates over the conterminous United States was performed using 60 FLUXNET station datasets (Velpuri, Senay, Singh, Bohms, & Verdin, 2013). Singh, Senay, Velpuri, Bohms, Scott, et al. (2014) and Singh, Senay, Velpuri, Bohms & Verdin (2014) created the first-ever basin-wide monthly and annual ET for 2010 for the entire Colorado River Basin (CRB) at the Landsat spatial scale using the SSEBop model.

One of the challenges of working with Landsat imagery is the large number of images required to cover an entire basin. For example, the CRB requires 43 Landsat scenes (path/row) each with a nominal area of about 180 km × 170 km. To obtain an annual ET estimate, each path/row has a potential of 22 images per year (assuming a single functional Landsat with a 16-day repeat cycle). Due to cloud cover, some of these 22 images may not be usable. This creates a differential number of usable images from year to year forcing the annual estimation to rely on interpolation techniques for the missing images.

The main objectives of the study are to (1) use Landsat 8 images to produce annual ET for the entire Colorado River Basin for 2013, (2) evaluate the performance of Landsat 8-derived ET using independent datasets such as eddy covariance (EC) and water balance ET approaches, and (3) assess the opportunities and challenges in using Landsat 8 for estimating basin-wide crop consumptive use towards meeting the USGS National Water Census objectives.

2. Data

We used various datasets from different sources ranging from field measurements to remotely sensed images for the Colorado River Basin (Fig. 1). A list of all datasets used in this study and their characteristics are provided in Table 1.

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