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Evapotranspiration by remote sensing: An analysis of the Colorado River Delta before and after the Minute 319 pulse flow to Mexico

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ABSTRACT

The unique hydrologic conditions characterizing riparian ecosystems in dryland (arid and semi-arid) areas help maintain high biodiversity and support high levels of primary productivity compared to associated uplands. In western North America, many riparian ecosystems have been damaged by altered flow regimes (e.g., impoundments and diversions) and over utilization of water resources (e.g., groundwater pumping for agriculture and human consumption). This has led some state and national governments to provide occasional environmental flows to address the declining condition of such riparian systems. In a historic agreement between the United States and Mexico, 130 million cubic meters (mcm) of water was released to the lower Colorado River Delta in Mexico, with the intent to evaluate the hydrological and biological response of the ecosystem. We used the Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) to estimate long term (2000–2014) and short term (pre- and post-pulse; 2013 and 2014) evapotranspiration (ET; used herein as an indicator of plant health) of the delta's riparian corridor. We found the pulse flow helped reverse a decline in ET from 2011 to 2013, with a small, but statistically significant increase in 2014 ($P < 0.05$). ET was greater than 100 mcm in all years analyzed (even in years without surface flows) and exceeded surface flows in all years except 2000 (result of excess flows following an El Niño cycle in 1997) and 2014 (year of the pulse flow). Based on groundwater salinities and MODIS ET estimates, we estimated groundwater flow into the delta to be ~103 mcm. Shallow groundwater salinities in the riparian zone increased from 1.30 g L^{-1} in the most upstream reach to 2.77 g L^{-1} in the most downstream reach we measured, partly due to uptake of water by riparian vegetation and partly to intrusion of saline agricultural return flows. The disparity between surface flows and ET can likely be explained by the predominantly phreatophytic plants characterizing the area, which draw water from the aquifer. These results also suggest that the deteriorated condition of vegetation within the riparian zone might not be reversed by a single pulse event and could instead require subsequent pulse flows as a long term strategy to restore vegetation in this riparian ecosystem.

1. Introduction

1.1. Water balance and evapotranspiration

The uniquely shallow groundwater and surface flows characterizing dryland riparian ecosystems help support high biodiversity and primary production in these otherwise water-limited ecosystems (Brown, 1982); therefore, the development of water budgets (balances) is important in the management of these areas (e.g., Goodrich et al., 2000). Depending on the region, scale, and local conditions, the role of actual evapotranspiration (ET), precipitation, runoff, and groundwater recharge on the water balance of an area can differ markedly (Wilcox et al., 2003). In water-limited ecosystems, precipitation is often the primary contributor to the water balance, where rain or snowmelt in the mountains is transferred to lower regions as surface or groundwater flows (Shen and Chen, 2010). In the mountains of western North America, snowmelt alone accounts for 50–80% of runoff (Stewart et al., 2004). Therefore, as aridity and the distance from such watersheds increases, the significance of upstream runoff becomes increasingly important in

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maintaining riparian ecosystems. In these environments, water is primarily lost through ET, with potential ET exceeding precipitation (Wilcox et al., 2003). For this reason, ET in drylands is an important component of the water budget and is a useful indicator of vegetation health.

Though many methods exist for assessing ET, the use of remote sensing-based vegetation index (VI) approaches has increased in recent years. One such VI is the Enhanced Vegetation Index (EVI). Combined with local meteorological data, EVI can be used as a surrogate for leaf area index (LAI), allowing for estimation of ET (e.g., Nagler et al., 2013; see Section 2.4 for a full explanation of EVI-based ET estimation). Over large areas, EVI from the Moderate Resolution Imaging Spectrometer (MODIS) sensor onboard NASA's Terra Satellite has shown to be particularly effective at estimating ET (Nagler et al., 2005a, 2013, 2016). Unlike the more commonly used Normalized Difference Vegetation Index (NDVI), EVI is less prone to saturation and responds more to characteristics like LAI and canopy structure (Gao et al., 2000). In addition to this, MODIS has robust temporal and spatial coverage, making it an efficient platform for assessing ET over large areas and varying time scales.

1.2. Study objectives

This study was conducted in the riparian corridor of the Colorado River (CR) Delta in Mexico (Fig. 1). This section of the CR once had perennial water flows, but due to impoundments, diversions, and consumptive uses, it typically only experiences surface flows during years of excess runoff (Glenn et al., 2001a). Despite reduced flows, the delta's riparian zone is an important migration corridor for a number of migratory bird species (Hinojosa-Huerta et al., 2013), including the endangered southwestern willow flycatcher (*Empidonax traillii extimus*; Glenn et al., 2001b). South of the Grand Canyon, the lower CR supports the largest area of riparian habitat in the Sonoran Desert (Glenn et al., 1996; Ohmart et al., 1988). Nagler et al. (2008) showed that even in years without surface flows the riparian corridor supports a mix of salt-tolerant and mesic riparian species, presumably due to underflows of fresh water from the U.S. and agricultural return flows from Mexico into the shallow riparian aquifer.

During the spring of 2014, the United States and Mexico released 130 million cubic meters (mcm) of water to the lower CR in Mexico, with the intent to evaluate the hydrological and biological response of the ecosystem (IBWC, 2014). Because of upstream diversions, this portion of the CR is usually dry, with water previously not having reached the Sea of Cortez since yr. 2000 (IBWC, 2014). The pulse was released from 23 March to 18 May 2014 to simulate historical flow events, although at a much lower volume. It inundated ~1830 ha of channel and floodplain and flow decreased rapidly as distance downstream increased, with less than 1% of the total pulse mixing with tidal waters in the Gulf of California (IBWC, 2014). River stage increased to a maximum of 5.96 m from 29 to 30 Mar. in the most upstream portion of the study area (Reach 1) to about 1.6 m on 11 May in the most downstream portion surveyed (Reach 5; Ramírez-Hernandez et al., in prep.). By 24 May 2014 surface flow from the pulse ceased (IBWC, 2014). The water table rose in response to the pulse across all segments (reaches) measured (IBWC, 2014), with an increase of 0.90–6.60 m in Reach 1 and about 0.30 m in Reach 5 (Kennedy et al., 2017). In order to assess the vegetation response to the pulse flow and to develop a conceptual model of the riparian hydrological system, we estimated ET using meteorological data and a MODIS EVI algorithm. The ET estimates were also combined with salinity data to estimate total flow into and out of the shallow riparian aquifer. We compare trends in ET from 2000 to 2014, encompassing a period of drought from 2000 to 2013 followed by the pulse flow of 2014.

2. Materials and methods

2.1. Study area

We studied the region of the CR Delta extending from the Morelos Dam at the US-Mexico border (the primary release point of the pulse) to just north of the Sea of Cortez (Fig. 1). Our study focused on the riparian zone (corridor) of the delta, which constituted 31,225 ha and was flanked along much of the east and west by agricultural fields. This region is exceptionally dry, with the watershed averaging ~60 mm rainfall per year (IBWC, 2006). We divided the study region (riparian corridor) into seven reaches based on geomorphic features (Fig. 1; see IBWC (2014) for a description of each reach). Vegetation from the Northerly International Boundary (NIB) to the confluence with the Rio Hardy (Fig. 1) was dominated by salt-tolerant saltcedar (*Tamarisk ramosissima*), with arrowweed (*Pluchea sericea*) shrubs, mesic native willow (*Salix gooddingii*), and cottonwood (*Populus fremontii*) also present (Glenn et al., 2001b). South of the Rio Hardy-CR confluence the predominant vegetation was saltcedar, but common reed (*Phragmites australis*) and cattail (*Typha domingensis*) were also prominent where standing water marshes formed from agricultural return flows (Glenn et al., 2001b). From the NIB to the Rio Hardy, the CR flows intermittently, with flows primarily occurring during times of above average precipitation in the upper basin source area; however, south of the Rio Hardy to the Sea of Cortez the CR is perennial due to agricultural return flows and treated municipal effluent in the Rio Hardy.

2.2. Riparian zone mask development

We used a two-step approach to creating a mask (polygon) representing the CR Delta's riparian zone. First, we used aerial imagery available within the Basemap feature in ArcGIS v10.2 (ESRI, Inc., Redlands, CA) to initially digitize the seven reaches comprising the riparian zone (typically bordered by levees or agricultural fields), while excluding occasional agricultural fields occurring within the levees. Second, because the basemap imagery in ArcGIS represented a single point in time, we imported the polygon into Google Earth (Google Inc.) and used the time slider function to identify and exclude all agricultural fields present in the available historical imagery (for all available images taken from 2001-present; Google Earth, Google Inc.). This process helped ensure we excluded all agricultural fields that were active during the time period of study, while enforcing topology rules in ArcGIS.

2.3. Data acquisition and extraction

In order to estimate ET for the CR Delta riparian zone, we used 16-d MODIS EVI (MOD13Q1 product) obtained using the MODIS Global Subsetting Tool from Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics (ORNL DAAC, 2015). See Section 2.4 (below) for a full discussion of MODIS EVI data. We selected a 99 × 99 km area encompassing the study region and generated 250 m GeoTIFFs re-projected to geographic latitude/longitude (WGS 84). We analyzed EVI scenes (GeoTIFFs) from the time of inception of the MODIS Terra satellite (18 Feb., 2000) to 19 Dec., 2014 (342 scenes).

All data manipulation and extraction operations were performed using ArcGIS v10.2 and v10.3. Prior to extracting EVI values for the study area, we converted the riparian mask polygon file to a raster using the Polygon to Raster tool, generating a 250 m cell raster representing all seven reaches within the riparian corridor. The mask raster was snapped (registered) to the MODIS scenes to ensure pixel alignment. We then reclassified the mask raster to a single value representing the entire riparian corridor. Using Raster Calculator, we removed standing water from each MODIS scene