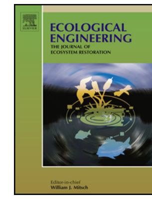
Ecological Engineering 59 (2013) 176–184

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Evapotranspiration and water balance of an anthropogenic coastal desert wetland: Responses to fire, inflows and salinities

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A R T I C L E   I N F O

Article history:
Received 10 April 2012
Received in revised form 31 May 2012
Accepted 22 June 2012
Available online 21 July 2012

Keywords:
Cattail
Common reed
MODIS
Remote sensing
Wetland water budget
Salinity
Colorado River delta

A B S T R A C T

Evapotranspiration (ET) and other water balance components were estimated for Cienega de Santa Clara, an anthropogenic brackish wetland in the delta of the Colorado River in Mexico. The marsh is in the Biosphere Reserve of the Upper Gulf of California and Delta of the Colorado River, and supports a high abundance and diversity of wildlife. Over 95% of its water supply originates as agricultural drain water from the USA, sent for disposal in Mexico. This study was conducted from 2009 to 2011, before, during and after a trial run of the Yuma Desalting Plant in the USA, which will divert water from the wetland and replace it with brine from the desalting operation. The goal was to estimate the main components in the water budget to be used in creating management scenarios for this marsh. We used a remote sensing algorithm to estimate ET from meteorological data and Enhanced Vegetation Index values from the Moderate Resolution Imaging Spectrometer (MODIS) sensors on the Terra satellite. ET estimates from the MODIS method were then compared to results from a mass balance of water and salt inflows and outflows over the study period. By both methods, mean annual ET estimates ranged from 2.6 to 3.0 mm d^{-1}, or 50 to 60% of reference ET (ET_o). Water entered at a mean salinity of 2.6 g L^{-1} TDS and mean salinity in the wetland was 3.73 g L^{-1} TDS over the 33 month study period. Over an annual cycle, 54% of inflows supported ET while the rest exited the marsh as outflows; however, in winter when ET was low, up to 90% of the inflows exited the marsh. An analysis of ET estimates over the years 2000–2011 showed that annual ET was proportional to the volume of inflows, but was also markedly stimulated by fires. Spring fires in 2006 and 2011 burned off accumulated thatch, resulting in vigorous growth of new leaves and a 30% increase in peak summer ET compared to non-fire years. Following fires, peak summer ET estimates were equal to ET_o, while in non-fire years peak ET was equal to only one-half to two-thirds of ET_o. Over annual cycles, estimated ET was always lower than ET_o, because *T. domingensis* is dormant in winter and shades the water surface, reducing direct evaporation. Thus, ET of a *Typha* marsh is likely to be less than an open water surface under most conditions.

1. Introduction

1.1. Wetland water budgets and the role of evapotranspiration

The water budget of a wetland determines its aerial extent, ecology, water quality, carbon storage, rates of ground water recharge or discharge and outflows into adjacent ecosystems (Bijoor et al., 2011; Bridgham et al., 2006; Mitsch and Gosslink, 2000). However, constructing accurate water budgets for wetlands can be difficult, and generalizations about wetland hydrology are prone to error (Bullock and Acreman, 2003). Evapotranspiration (ET) is often the largest discharge term in a wetland water budget, and can be especially difficult to estimate (Drexler et al., 2004). For wetlands dominated by emergent vegetation, there is a debate about the magnitude of wetland ET in relation to reference crop ET (ET_o) (Allen et al., 1998) and the relative importance of plant transpiration and open-water evaporation in contributing to wetland ET (Drexler et al., 2004, 2008; Bijoor et al., 2011). Some studies show

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http://dx.doi.org/10.1016/j.ecoleng.2012.06.043

that the presence of wetland reed vegetation elevates ET above ET_o from an open water surface, by increasing the evaporative surface area through high leaf area index (LAI) (e.g., Towler et al., 2004), while others report that wetland ET is approximately equal to open-water evaporation or ET_o (e.g., Drexler et al., 2008; Farnsworth and Meyerson, 2003; Sun et al., 2010), and yet others report that wetland ET is generally lower than ET_o due to constraints on stomatal conductance of leaves and shading of the water surface by the canopy (e.g., Bijoor et al., 2011; Goulden et al., 2007; Lenters et al., 2011).

Emergent wetlands can differ markedly in their ecohydrology, depending on dominant species, salinity, water depth and other environmental factors (Bullock and Acreman, 2003; Jolly et al., 2008), explaining much of the discrepancy in ET among studies. However, part of the controversy is also due to differences in methods to estimate wetland ET (reviewed in Drexler et al., 2004).

1.2. Methods for estimating wetland ET

Traditionally, ET of wetlands has been estimated as a residual in water balance equations, when inflows, outflows, precipitation, change in storage and ground water discharge or recharge rates can be estimated (Environmental Protection Agency, 1998; Mitsch and Gosslink, 2000; Jia et al., 2011). Under ideal conditions the water balance approach can provide an accurate estimate of ET over annual or long time periods, when seasonal changes in storage become negligible, especially for wetlands with well-defined inflows and outflows (e.g., Bedford et al., 1999). More recent advances in measuring wetland ET include moisture flux towers (Goulden et al., 2007; Zhou et al., 2010), scintillometry (Lenters et al., 2011), surface renewal methods based on heat fluxes over the canopy (Drexler et al., 2004, 2008), diurnal fluctuations in ground water levels (Mould et al., 2011), remote sensing (Sun et al., 2010) and micrometeorological models (Drexler et al., 2004). These methods give real-time or near-real-time estimates that can reveal seasonal trends and environmental controls on ET. However, a review of these methods concluded that no one method is suited for all wetlands. Further, each method can have a potential error or uncertainty of 20–30%, and often no alternative method for independently validating ET estimates is available (Drexler et al., 2004).

1.3. Remote sensing and water budget approaches to estimating wetland ET in the present study

This study used a vegetation-index-based remote sensing method based on the Enhanced Vegeation Index from the Moderate Resolution Imaging Spectrometer (MODIS) on the Terra satellite (Huete et al., 2002, 2011), tested against a salt-and-water balance approach (Jia et al., 2011) to estimate ET and to construct a water balance for the Cienega de Santa Clara, a brackish *Typha*/*Phragmites* marsh in the delta of the Colorado River, Mexico (Glenn et al., 1992; Zengel et al., 1995). At approximately 5000 ha, this is perhaps the largest emergent marsh in the Sonoran Desert. It is supported mainly by flows of agricultural drainage water from the U.S., which discharge into the intertidal zone of the delta. It supports numerous species of water birds which use it as a nesting area and as a stopover site during their migration on the Pacific Flyway (Glenn et al., 2001). 80% of the remaining endangered Yuma Clapper Rails (an endangered marsh bird) nest in the Cienega (Hinojosa-Huerta et al., 2001, 2002). It provides a good case study for conducting a wetland water budget, because inflows are measured, and it is isolated from adjacent ecosystems (Huckelbridge et al., 2010).

1.4. Objectives of the study

The study was prompted by a test run of the Yuma Desalting Plant (YDP), which is expected to reduce inflows and increase the salinity of the water in the Cienega (Gabriel and Kelli, 2010). The test run was conducted in 2010, and an intensive monitoring program was conducted from 2009 to 2011 before, during and after the operation of the YDP to document biological and hydrological responses of the ecosystem to reduced flows and altered salinities (Flessa et al., 2012). The Cienega Monitoring Program conducted ground, aerial and satellite surveillance of the Cienega to document changes in the extent and vigor of the vegetation and to construct a water budget and a predictive model of the vegetation in response to changes in inflows and salinities. Flow gauges monitored the inflows of water to the marsh, and salinity was measured in the inflow water and at numerous recording stations throughout the vegetated area of the marsh. This allowed us to check the accuracy of the satellite-derived ET estimates by a mass balance approach (Jia et al., 2011), and to construct a water balance for the Cienega during operation of the YDP. The objectives of the study were to estimate the seasonal and inter-annual variations in ET from the marsh in response to inflows and environmental factors, and to create a water budget for the Cienega, which could ultimately be used as a management tool for predicting the ecosystem response to different operating scenarios of the YDP.

2. Materials and methods

2.1. Description of Cienega vegetation and hydrology

The Cienega is located at the north end of the Santa Clara Slough, a tidal basin formed where the Cerro Prieto fault line enters the Gulf of California (Fig. 1A). The Cienega is in a hot desert environment, with mean annual temperature of 23.3 °C and annual rainfall of 80 mm based on data from Yuma in the U.S., approximately 100 km to the north (AZMET, 2012). The southern end of the Santa Clara Slough is flushed approximately monthly by high tide events but tide water does not enter the Cienega (Flessa et al., 2012). The main source of water in the Cienega is the MODE canal, which discharges at the northern end of the marsh, along with a smaller volume of local drain water entering in the Riito canal (Fig. 1B). Water in the MODE canal has entered the wetland at a rate of approximately 4 $m^3 s^{-1}$ and 2–3 $g L^{-1}$ Total dissolved solids (TDS) since 1977, and the footprint of the marsh has been stable at about 5000 ha since 1995 (Zengel et al., 1995). *T. domingensis* is the dominant species, making up over 90% of the plant cover, while *P. australis* makes up 7% of the plant cover and 20 other species grow at lower densities along the edges of the marsh (Glenn et al., 1995; Zengel et al., 1995). Vegetation covers about 85% of the marsh area and open water lagoons cover and additional 15%; the lagoons are in areas of deeper water where emergent vegetation does not grow, and they have been stable features in the marsh since 1995 (Zengel et al., 1995). Fig. 1B shows the sampling stations for salinity measurements and locations where MODIS pixels were acquired to estimate ET.

The average depth of water in the Cienega is 0.32 m, but depths exceed 1 m in the open water lagoons (Flessa et al., 2012). At a mean inflow rate of 4 $m^3 s^{-1}$ from the MODE canal, the nominal detention time for water is 46 d. The flow of water appears to be predominantly through the middle of the marsh following the deeper water channel formed by the Cerro Prieto fault line (Zengel et al., 1995). The main outlet for water is at the southern end of the Cienega where water flows into the Santa Clara Slough, but water also spills out of the wetland at several points along the western edge (Fig. 1B).