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# Modeling water management scenarios for the Cienega de Santa Clara, an anthropogenic coastal desert wetland system, based on inflow volumes and salinities

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ABSTRACT

The Cienega de Santa Clara in the Colorado River Delta, Mexico is a self-designed wetland system fed since 1977 by brackish groundwater diverted from the U.S. to Mexico. The vegetated upper portion of the Cienega provides habitat for endangered Yuma-Clappers rails and other marsh birds and fulfills other ecological functions. Outflow water pools in the Santa Clara Slough south of the Cienega and provides habitat for migratory shorebirds. Conditions in the Cienega and Santa Clara Slough could be altered by operation of the Yuma Desalting Plant (YDP), which will divert water from the Cienega and replace it with brine water resulting from the desalting process. Our objective was to integrate water budget components into models predicting the extent of the dominant vegetation (southern cattail, *Typha domingensis* Pers.) in the marsh and the area of the outflow pool below the marsh in response to different operating scenarios for the YDP. The models are intended to serve as tools for resource managers charged with maintaining this wetland complex. Unlike many wetland water budget models, this one explicitly takes into account salinity as a factor in the water budget. We modeled inflow rates ranging from 1 to 6 $m^3 s^{-1}$ and inflow salinities ranging from 0 to 6 $g L^{-1}$ Total Dissolved Solids. The model indicates that if the inflow rate is reduced below the current 4–5 $m^3 s^{-1}$ the vegetated area of the Cienega would decrease in proportion, as would the area of the outflow pool in the Santa Clara Slough. Increases in salinity will also reduce the vegetated area due to the low salt tolerance of *T. domingensis*. In winter about 90% of inflow water exits the Cienega into the Santa Clara Slough due to low evapotranspiration, and on an annual basis 70% of inflows exit into the Santa Clara Slough. These flushing flows maintain the salt balance in the Cienega. The Santa Clara Slough is periodically flushed by spring tides, making this a sustainable, open wetland system in its present state.

## 1. Introduction

### 1.1. Background

The Cienega de Santa Clara is a large self-designed wetland system of about 20,000 ha in the eastern portion of the Colorado River delta in Mexico that depends in part on brackish water delivered from United Stated to Mexico (Mexicano et al., 2013; Glenn et al., 2012; Greenberg and Schlatter, 2012) (Fig. 1). The wetland system consists of a vegetated marsh of about 5000 ha dominated by southern cattail (*T. domingensis* Pers.) (designated the Cienega in this paper) and a shallow, unvegetated pool of variable area south of the vegetation, fed by Cienega outflows and tide water (designated the Santa Clara Slough in this paper) (Glenn et al., 1992, 1995; Zengel et al., 1995). Both are within the core area of the Biosphere Reserve of the Upper Gulf of California and delta of the Colorado River, and are internationally significant for providing marsh bird habitat in the Cienega in spring and summer and shorebird habitat in the Santa Clara Slough in winter (Hinojosa-Huerta et al., 2001a,b, 2002; Greenberg and Schlatter, 2012; Gomez-Sapiens et al., 2013). Other threatened and endangered species are also found in the Cienega (e.g., Zengel and Glenn, 1996).

Most water enters the Cienega in the Main Outlet Drain Extension (MODE) canal (also called the Bypass Drain), which since 1977 has sent brackish agricultural return flows from the Wellton-Mohawk Irrigation District in the U.S. to the delta in Mexico for

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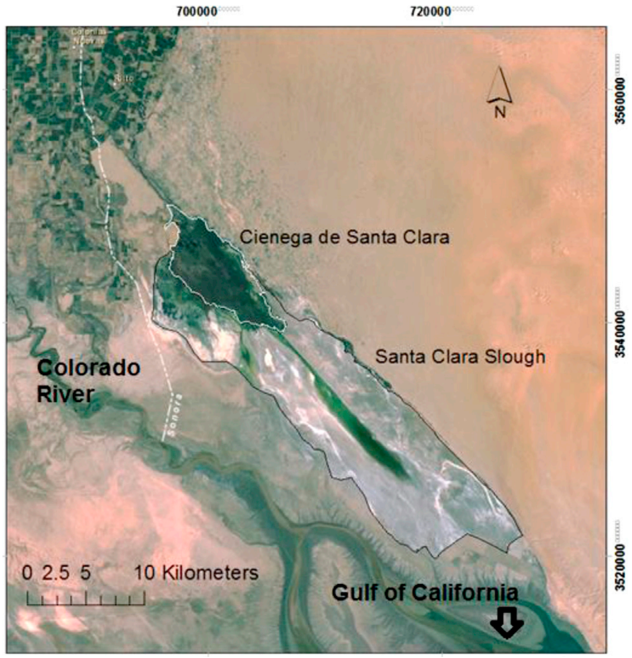

**Fig. 1.** Satellite image of Cienega and Santa Clara Slough in the Colorado River delta.

disposal (Greenberg and Schlatter, 2012). A much smaller flow enters from the Riito Drain, which collects local agricultural drain water (see Table 1). The MODE discharge was intended to be temporary pending completion of the Yuma Desalination Plant (YDP), which was designed to desalinate MODE water for delivery to Mexican agricultural fields. The MODE was then intended to carry brine from the YDP, containing salts from the desalination process, for disposal in Mexico (Leitz and Ewoldsen, 1977; Haugseth, 1978; Lohman, 2003). However, since its completion in 1992 the YDP has only been operated during a few brief test runs and the flow of brackish agricultural return water has continued largely without interruption, contributing to development of a wetland of international importance in the delta (Greenberg and Schlatter, 2012).

US and Mexican agencies collaborated to implement a monitoring program from 2009 to 2011 with the aim of gathering information about the hydrology, weather, physical attributes and biological resources of the wetland (Peters et al., 2009; Greenberg and Schlatter, 2012). This information is expected to be used to understand the main ecosystem processes and analyze management alternatives for the Cienega. In particular, information is needed on effects to the Cienega should the YDP become operational. A range of operating scenarios for the YDP have been contemplated (e.g., Blank, 2007), with different potential impacts on the volume and salinity of flows into the Cienega. The present study developed simple models to predict the changes in the area of the dominant vegetation type, *T. domingensis* (southern cattail) in the Cienega and the surface area of the outflow pool in the Santa Clara Slough in response to different operating scenarios of the YDP.

**Table 1**
Mean and standard errors of hydrological parameters used in estimating ET by a water budget equation, compared to ET estimating by MODIS satellite imagery (from Glenn et al., 2012).

| Parameter | Mean (std. error) |
|---|---|
| Flows in ($m^3 s^{-1}$) | |
| MODE | 4.75 (0.18) |
| Riito | 0.21 (0.08) |
| Precipitation | 0.013 |
| Total in ($m^3 s^{-1}$) | 4.97(0.19) |
| TDS in ($g L^{-1}$) | |
| MODE | 2.59 (0.06) |
| Riito | 3.46 (0.15) |
| Precipitation | 0.0 |
| Weighted mean TDS in ($g L^{-1}$) | 2.62 (0.07) |
| TDS mean Cienega ($g L^{-1}$) | 3.73 (0.08) |
| ET by mass balance ($mm d^{-1}$) | 2.62 (0.11) |
| ET by MODIS ($mm d^{-1}$) | 2.97 (0.16) |

### 1.2. Importance of salinity in wetland water budgets

One of the basic approaches in the understanding of wetlands structure and function is to estimate the water balance (Mitsch and Gosselink, 2000). Once the water balance is established it is possible to model the response of the wetland to hydrological and weather parameters, to simulate the implementation of management schemes and to understand the response of the ecosystem to natural events (Carter, 1986; Zacharias et al., 2005; Zhang and Mitsch, 2005; Huckelbridge et al., 2010; Jia et al., 2011).

In arid and semiarid ecosystems, high evapotranspiration rates can increase the salinity of wetlands and other sensitive ecosystems (Cramer and Hobbs, 2002; Jolly et al., 2008). Salinity effects are especially important in wetlands such as the Cienega that receive saline agricultural return flows. Problems of elemental toxicity and elevated salinities have developed in some wetlands receiving saline agricultural return flows, calling into question their sustainability and safety (Lemly et al., 1993; Lemly, 1994). Even though the transport of salinity is critical in these systems, in most cases, the salt transport pathways in wetlands are not very clear and are rarely incorporated in water budget models (Bauer et al., 2006; Jolly et al., 2008; Jia et al., 2011). In the Cienega, the salts (mainly sodium, calcium, chlorine and sulfate) enter through the inflow at a 2–3 $g L^{-1}$ Total Dissolved Solids (TDSs) average concentration (Haugseth, 1978). Due to the relatively low salt-tolerance of the dominant vegetation (Baeza et al., 2012), we consider salt inputs need to be included in a water budget model for the Cienega.

### 1.3. Aims and objectives of the study

The aim of this work was to integrate water budget variables, to include inflow rate, outflow volume, salinity concentration of the inflow, vegetation salinity threshold and evapotranspiration (ET), into simplified models that can be useful to predict the responses of the Cienega and Santa Clara Slough to different scenarios of water quality and volumes. The Cienega de Santa Clara wetland system is isolated from surrounding systems with relatively well-defined inputs and outputs, and baseline data were available from 2009 to 2011 to parameterize and partially validate the models. The results present a case study of how alterations in flow and salinities due to land use change or climate change can impact both anthropogenic and natural brackish coastal wetlands, and how management practices can mitigate damage.

## 2. Methods

### 2.1. System description

The Cienega is an emergent marsh, 89% of which is vegetated. The remainder of the marsh is composed of 543 open-water lagoons scattered amidst the emergent plant stands, ranging in size from <1 ha to about 20 ha in area. *T. domingensis* accounts for about 90% of vegetation cover and patches of common reed (*Phragmatis australis*) make up about 7% of the vegetation, growing in shallow areas within the marsh (Glenn et al., 1992; Zengel et al., 1995; Mexicano et al., 2013). Twenty other hydrophytes occur within and around the Cienega (Glenn et al., 1995; Zengel et al., 1995). Mean water

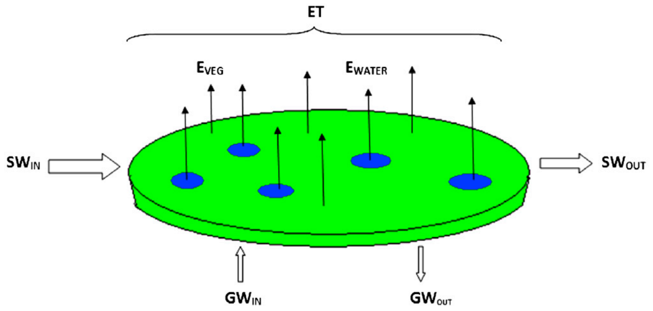

**Fig. 2.** Schematic of the Cienega vegetated area showing water budget components. $SW_{IN}$, surface water inflow; $SW_{OUT}$, surface water outflow; $E_{VEG}$, transpiration by vegetation; $E_{WATER}$, evaporation from open water areas; ET, total evapotranspiration; $GW_{IN}$, groundwater inflows; $GW_{OUT}$, groundwater outflows.

depth is 0.32 m but exceeds 1 m in the open water lagoons, and is only a few cm deep along the perimeter, which changes location according to inflow rates and rates of evaporation (Greenberg and Schlatter, 2012). Open water lagoons cover 11% of the Cienega and support submerged aquatic plants such as *Najas marinas* and *Ruppia maritima*. The thick *T. domingensis* stands support 80% of the remaining Yuma clapper rails (*Rallus longirostris yumanensis*), an endangered marsh bird that nests in the Cienega in spring and summer (Hinojosa-Huerta et al., 2001a, 2002). A smaller number of endangered black rails are also found in the Cienega (Hinojosa-Huerta et al., 2001b).

The lower basin Santa Clara Slough is a shallow (ca 0–0.3 m depth) evaporation lagoon that varies in size in response to the season, tides and water entering from the Cienega (Nelson et al., 2013). In this unvegetated wetland the incoming brackish water mixes with sea water during occasional high tide events (above 5.2 m, occurring approximately 8–10 times per year) (Nelson et al., 2013). Much of the water that enters the Santa Clara Slough evaporates within the basin, making this a hypersaline wetland when flooded. It is an important feeding station for migratory shorebirds in winter, with annual visitation by several hundred thousand birds per year (Gomez-Sapiens et al., 2013).

The Cienega and Santa Clara Slough are in the most arid portion of the Sonoran Desert in the Lower Colorado River Valley Subdivision (Shreve and Wiggins, 1964). Average annual precipitation is 68 mm, and average temperature of 25 °C with rain events in both summer and winter (Miranda-Reyes et al., 1990).

### 2.2. General modeling approach

Models were based on the steady-state water balance equation for wetlands (Mitsch and Gosselink, 2000):

$$SW_{IN} + P + GW_{IN} - ET - SW_{OUT} - GW_{OUT} - \Delta S = 0 \quad (1)$$

where $SW_{IN}$ is surface water inflow, $P$ is precipitation, $GW_{IN}$ is ground water in, ET is evapotranspiration, $SW_{OUT}$ is surface water outflow, $GW_{OUT}$ is ground water outflow and $\Delta S$ is change in storage in the wetland (shown schematically in Fig. 2).

Salinity relationships were based on equations developed by Jia et al. (2011), who defined a coefficient, $\beta$, as:

$$\beta = \frac{SW_{OUT}}{SW_{IN}} = \frac{C_{IN}}{C_W} \quad (2)$$

where $C_W$ is the mean salinity in the wetland, and $C_{IN}$ is the salinity of the inflow water. Eq. (2) accounts for the increase in salinity that occurs as water from the wetland is discharged in ET, which reduces the outflow volumes and increases the salinity in the wetland, because pure water is discharged in ET. As an example, if half the inflow water exits the marsh as surface flows or net groundwater discharge, and the other half is discharged in ET, $\beta = 0.5$, and if the inflow salinity is $2\,g\,L^{-1}$, the mean wetland salinity is $4\,g\,L^{-1}$. In the Jia et al. (2011) model $C_W$ is corrected for the uptake of salt into vegetation, which is harvested in their model system, but in the Cienega salts in vegetation are expected to be a small term in the overall water budget. Based on an annual production rates and salt contents of *T. domingensis* reported in Baeza et al. (2012), uptake of salts into vegetation could account for only 1.2% of salts in inflow water, and these salts are expected to be recycled within the wetland as litter decays or burns, hence this factor is not included in Eq. (2). Groundwater exchange is also not included in Eq. (2) due to lack of data (Flessa and García-Hernández, 2007). However, groundwater exchanged is also expected to be a small term compared to inflows, and no net exchange of salts between surface water and groundwater is expected at equilibrium (Jia et al., 2011). Eq. (2) allowed us to estimate ET and $SW_{OUT}$ from $C_{IN}$ and $C_W$.

Values for the water balance components were based on monthly measurements made over a 33-month period, 2009–2011, and are listed in Table 1 (Greenberg and Schlatter, 2012; Glenn et al., 2012). The area of vegetation and open water were determined on a April 24, 2009 Quickbird (0.6 m resolution, Digital Globe, Inc., Longmont, CO) satellite image (Mexicano et al., 2013). The total area (4913 ha) ($A_{WETLAND}$) contained 4395 ha of vegetation ($A_{VEG}$), mostly *T. domingensis*, and 518 ha of open water lagoons ($A_{WATER}$). Total flows into the Cienega were approximately $2.7 \times 10^8\,m^3$ during the 33 month measurement period, 17 times greater than the volume of the Cienega (approximately $1.6 \times 10^7\,m^3$), justifying the assumption that changes in storage volume ($\Delta S$) were negligible compared to inflows and outflows over annual or longer time periods, a requirement for steady-state water budgets (Jia et al., 2011). $GW_{IN}$ and $GW_{OUT}$ were not measured, but were assumed to be in equilibrium over annual or longer time periods (Jia et al., 2011). This assumption was supported by a mass balance of surface flows, showing that inflows minus outflows could be accounted for by losses due to ET as estimated by a remote sensing technique (Glenn et al., 2012).

ET was divided into two components, transpiration by vegetation ($E_{VEG}$) and open water evaporation ($E_{WATER}$). $E_{VEG}$ and $E_{WATER}$ were expressed in rate units of $m^3\,m^{-2}\,month^{-1}$, and total ET in units of $m^3\,month^{-1}$ was calculated as:

$$ET = (0.89E_{VEG} + 0.11E_{WATER})A_{WETLAND} \quad (3)$$

Eq. (3) holds the proportion of vegetation to open water, measured in 2009, constant over the different scenarios modeled in this study.

$E_{VEG}$ was estimated at 16-d intervals using the Enhanced Vegetation Index (EVI) from the Moderate Resolution Imaging Spectrometer (MODIS) sensors on the Terra satellite and estimates of potential ET ($ET_o$) calculated by the Blaney–Criddle formula (Brouwer and Heibloem, 1986) from temperature data from the Yuma Valley AZMET station (AZMET, 2012), about 100 km from the Cienega in Arizona, U.S. (Glenn et al., 2012). $E_{VEG}$ was calculated using the method developed by Nagler et al. (2009):

$$E_{VEG} = 1.22ET_o(EVI^*) \quad (4)$$

where EVI* is EVI scaled between bare soil EVI ($EVI_{min}$), assumed to have zero transpiration, and the EVI of dense, unstressed vegetation ($EVI_{max}$), assumed to be transpiring at the rate of $ET_o$. EVI* was calculated as:

$$EVI^* = 1 - \frac{EVI_{max} - EVI}{EVI_{max} - EVI_{min}} \quad (5)$$

EVI values of 0.091 and 0.542 were used for $EVI_{min}$ and $EVI_{max}$ based on a large data set from previous studies (Nagler et al., 2005a,b). 1.22 is a regression coefficient relating $E_{VEG}$ to $ET_o$ and EVI* based on ground values of $E_{\mathrm{VEG}}$ measured for riparian and agricultural plants on the Lower Colorado River in a previous study (Nagler et al., 2009). It had a standard error of 20% in predicting $E_{\mathrm{VEG}}$ of different plant types in that study.

$E_{\mathrm{WATER}}$ was assumed to be equal to $\mathrm{ET_o}$ (Huckelbridge et al., 2010; Glenn et al., 2012). As justification, annual evaporation from the Salton Sea (150 km from the Cienega), for which evaporation data are available, is 1798 mm per year (Ponce, 2005), compared to our estimate of $\mathrm{ET_o}$ of 1820 mm per year for the Cienega based on Yuma AZMET data (AZMET, 2012). $\mathrm{SW_{IN}}$ was the sum of MODE canal water (data from the International Boundary and Water Commission, El Paso, Texas), precipitation (from the Yuma Valley AZMET station) and sporadic flows in the Riito canal carrying local irrigation return flows (gagged during the study period) (Greenberg and Schlatter, 2012). During the study period, MODE canal water accounted for over 95% of $\mathrm{SW_{IN}}$. Salinity data for MODE water was from the International Boundary and Water Commission. Salinity in the Riito canal and at 22 points in the Cienega were measured during field surveys monthly with hand-held electrical conductivity meters calibrated with gravimetric measurements of TDS in the laboratory (Greenberg and Schlatter, 2012).

### 2.3. *Modeling vegetated area in response to inflow volumes and salinities*

Different approaches were used to model the areal extent of *T. domingensis* vegetation in the Cienega and the outflows from the Cienega. The Cienega vegetation model was a steady state, empirical model based on the salt tolerance limit of *T. domingensis*, which determined the fraction of inflow water that could support *T. domingensis* growth and ET:

$$\mathrm{SW_{IN\text{-}Usable}} = \frac{\mathrm{SW_{IN}}(C_{\mathrm{Threshold}} - C_{\mathrm{IN}})}{C_{\mathrm{Threshold}}} \quad (6)$$

where $\mathrm{SW_{IN\text{-}Usable}}$ is the flow rate of inflow water that can support transpiration of *T. domingensis* (e.e., $E_{\mathrm{VEG}}$), $C_{\mathrm{IN}}$ is salinity of inflow water and $C_{\mathrm{Threshold}}$ is the salinity limit for growth and transpiration of *T. domengensis*. Eq. (6) was originally developed to predict annual ET and yield of crop plants grown on saline water based on the salt tolerance threshold of a given crop (Shani and Dudley, 2001; Dudley et al., 2008). Its application to the Cienega was validated in Glenn et al. (2012) which used mass balance and remote sensing methods to compute water balance components of the marsh. Based on greenhouse and field studies in the Cienega (Glenn et al., 1995; Baeza et al., 2012) and literature values (Hocking, 1981; Beare and Zedler, 1987), $C_{\mathrm{Threshold}}$ was set at 6.0 in our model. As a sample calculation, if water enters at 3 g $\mathrm{L^{-1}}$ TDS, the usable fraction is (6–3)/6, or 0.5. The remainder is assumed to exit the Cienega as outflow, or to be discharged as evaporation from open water lagoons ($E_{\mathrm{WATER}}$). When $C_{\mathrm{IN}}$ is 0 g $\mathrm{L^{-1}}$ TDS, $\mathrm{SW_{IN\text{-}Usable}}$ is 1.0, while when $C_{\mathrm{IN}}$ is 6.0 g $\mathrm{L^{-1}}$ TDS, $\mathrm{SW_{IN\text{-}Usable}}$ is 0.0.

The maximum area of vegetation that could be supported by a given volume and salinity of inflow water was calculated based on the period 2009–2011, taken as a baseline, during which time $\mathrm{SW_{IN}}$ was 4.97 $\mathrm{m^3\,s^{-1}}$, $C_{\mathrm{IN}}$ was 2.62 g $\mathrm{L^{-1}}$ TDS, area of vegetation was 4395 ha, and $\mathrm{SW_{IN\text{-}Usable}}$ was calculated by Eq. (6) as 0.56 over the June–September period of maximum $E_{\mathrm{VEG}}$, when water availability was assumed to be limiting for determining the area of the wetland (Glenn et al., 2012). Then for any given scenario the area of vegetation was calculated as:

$$A_{\mathrm{VEG}} = \frac{4395[(6 - C_{\mathrm{IN}})/6]}{0.56(\mathrm{SW_{IN}}/4.97)} \quad (7)$$

and $A_{\mathrm{WETLAND}}$ is 1.12 ($A_{\mathrm{VEG}}$) to account for open water areas

**Table 2**
Values for $E_{\mathrm{VEG}}$ and $E_{\mathrm{WATER}}$ used in models in this study. For a given month, $E_{\mathrm{WATER}}$ was assumed to be equal to $\mathrm{ET_o}$ estimated by the Blaney–Criddle method based on meteorological data from the Yuma Valley, Arizona, AZMET station.

| Month | $E_{\mathrm{VEG}}$ ($\mathrm{m^3\,m^{-2}\,month^{-1}}$) | $E_{\mathrm{WATER}}$ ($\mathrm{m^3\,m^{-2}\,month^{-1}}$) |
|---|---|---|
| January | 0.025 | 0.101 |
| February | 0.022 | 0.125 |
| March | 0.024 | 0.138 |
| April | 0.040 | 0.162 |
| May | 0.070 | 0.210 |
| June | 0.121 | 0.217 |
| July | 0.152 | 0.215 |
| August | 0.121 | 0.199 |
| September | 0.089 | 0.170 |
| October | 0.057 | 0.134 |
| November | 0.041 | 0.115 |
| December | 0.021 | 0.095 |

Several simplifying assumptions are embedded in Eq. (7). First is that *T. domingensis* will continue to be the dominant vegetation type determining vegetated area under different salinity scenarios. However, the wetland also supports *Schoenoplectus* spp. (bulrushes), which are more salt tolerant than *Typha* spp. (Baeza et al., 2012) and they could replace *T. domingensis* in portions of the Cienega. Dense *T. domingensis* stands are required for support of breeding Yuma clapper rails (Hinojosa-Huerta et al., 2001a, 2002; Conway et al., 1993), hence the model provides a fair description of habitat availability for this and other marsh birds that require dense *Typha* stands, but cannot predict the eventual species composition of the marsh under altered salinity conditions. A second assumption is that $E_{\mathrm{VEG}}$ can be treated as a constant within the usable salinity range and $A_{\mathrm{VEG}}$ is only determined by the amount of usable water available in summer. However, at elevated salinities, $E_{\mathrm{VEG}}$ could be expected to decrease, leading to lower water use on a unit area basis and thus more areal coverage of vegetation at the high end of the salinity range than predicted by the model. Conversely, at lower salinities $E_{\mathrm{VEG}}$ could increase, leading to overestimates of vegetation cover at reduced salinities. However, $E_{\mathrm{VEG}}$ under reference conditions was only 50% of $\mathrm{ET_o}$ based on MODIS imagery and meteorological data, and appeared to be light-limited due to the accumulation of thatch within the stands (Glenn et al., 2012). Furthermore, when thatch was removed by fire in other years, peak ET over the wetland was equal to $\mathrm{ET_o}$ despite salinity constraints (Glenn et al., 2012). Hence, a reduced rate of $E_{\mathrm{VEG}}$ is already built into the reference conditions and no correction was applied to $E_{\mathrm{VEG}}$ under altered salinity conditions. Model assumptions and sources of error and uncertainty are discussed further in Section 4.3. Note also that Eqs. (2), (6) and (7) offer means of estimating $E_{\mathrm{VEG}}$ and $E_{\mathrm{WATER}}$ for comparison with MODIS estimates (see Section 3.1).

### 2.4. *Model for determining outflows and area of the outflow pool*

Unlike $A_{\mathrm{VEG}}$, which is expected to change slowly in response to inflows, $\mathrm{SW_{OUT}}$ changes throughout the year according to environmental evaporation rates and seasonal water demands of the vegetation. Therefore, $\mathrm{SW_{OUT}}$ was modeled in monthly time steps. According to Eq. (1), and assuming changes in groundwater and surface water storage are negligible at monthly time steps, $\mathrm{SW_{OUT}}$ can be estimated as:

$$\mathrm{SW_{OUT}} = \mathrm{SW_{IN}} - (E_{\mathrm{VEG}} \times A_{\mathrm{VEG}} + E_{\mathrm{WATER}} \times A_{\mathrm{WATER}}) \quad (8)$$

where $A_{\mathrm{VEG}}$ is calculated by Eq. (8). Monthly rates of $\mathrm{ET_{VEG}}$ and $\mathrm{ET_o}$ used in the model are in Table 2. As examples, for the month of

January 2009 the calculation is:

$$\begin{aligned}\mathrm{SW_{OUT}}(\mathrm{m^3\,month^{-1}}) &= 1.237\times10^7\,\mathrm{m^3} - (0.025\,\mathrm{m^3\,m^{-2}} \\ &\quad \times 4.395\times10^7\,\mathrm{m^2} + 0.101\,\mathrm{m^3\,m^{-2}}\times5.18\times10^6\,\mathrm{m^2}) \\ &= 1.075\times10^7\,\mathrm{m^3\,month^{-1}}\end{aligned} \tag{9}$$

whereas for June 2009 the calculation is:

$$\begin{aligned}\mathrm{SW_{OUT}}\ (\mathrm{m^3\,month^{-1}}) &= 1.33\times10^7 - (0.121\,\mathrm{m^3\,m^{-2}} \\ &\quad \times 4.395\times10^7\,\mathrm{m^2} + 0.217\times5.18\times10^6\,\mathrm{m^2}) \\ &= 6.442\times10^6\,\mathrm{m^3\,month^{-1}}\end{aligned} \tag{10}$$

These examples show that in winter, when ET is low, most of the water exits the Cienega as outflow (87% in January 2009), whereas in summer, when ET is high, outflow is reduced (51% in June 2009), presumably representing the fraction that is too saline to support $E_{\mathrm{VEG}}$.

### 2.5. *Estimating the area of the outflow pool in the Santa Clara Slough*

The area of the Santa Clara Slough tide basin is approximately 36,000 ha but the inundated area is normally much smaller. The area of the outflow pool is dependent on the rate of outflow from the Cienega, the water depth, the evaporation rate, and the geometry of the basin. None of these variables were directly measured. Furthermore, the Santa Clara Slough also receives water from extreme high tide events that bring in water from the Gulf of California. When flooded to its maximum extent the water surface of the Santa Clara Slough covers as much as 36,000 ha, but the pool area is typically much smaller, ranging from 0 in summer to approximately 15,000 ha following extreme spring tides in winter.

We approximated the pool size that could result from outflows from the Cienega and compared them to satellite imagery obtained at different times of year to attempt to determine the contribution that Cienega outflows make to shorebird habitat. We modeled the basin as a section of a sphere with a mean depth of 0.15 m, varying from 0 m at the margins to 0.3 m in the center (Fig. 3), based on estimates from aerial and ground observations at different times of year by anecdotal evidence from several observers who have canoed through the Slough when it is full (Nelson et al., 2013). The controlling equations (Fig. 3) show that as water evaporates, the surface area decreases in direct proportion to the decrease in water depth. An iterative procedure was used to estimate the potential water surface area attributable to Cienega outflows in monthly time steps. For the initial month (January 2009), an initial area was calculated based on the volume of inflows and assuming an initial maximum depth (*h* in Fig. 3) of 0.30 m. Then the monthly rate of $\mathrm{ET_o}$ (Table 1) was used to decrease the area in proportion to the amount evaporated during the month. The final pool size at the end of the month was then added onto the next month's initial area determined by that month's inflows, and the final area was adjusted downward according to that month's $\mathrm{ET_o}$. The hypothetical pool areas were estimated for the period 2009–2010, using an initial value of 4400 ha based on January 2009 inflows and assuming no carry-over from the previous month. Then the December 2010 pool area was used as input to subsequent iterations of the model. Three iterations of the calculation chain were sufficient to produce stable monthly values.

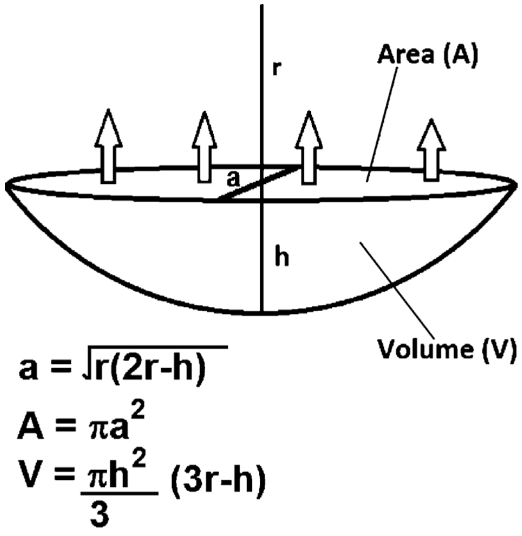

**Fig. 3.** Method for calculating surface area of the Santa Clara Slough supported by outflows from the Cienega, based on volume and area relations of a spherical section. Small letter *a* is the radius of the cap; *h* is the height of the cap; *r* (including segment *h*) is the radius of the sphere. Arrows represent water lost to evaporation; as water evaporates Area *A* decreases in proportion to the decrease in *h*. Formulas from Wolframs Mathworld, http://mathworld.wolfram.com/SphericalCap.html.

### 2.6. *Santa Clara Slough pool area estimated by MODIS imagery*

MODIS images are acquired at near-daily intervals at approximately 10:30 a.m. in descending mode in the Colorado River delta. A collection of daily images representing different tide conditions from 2009 to 2011 was obtained from NASA's Rapid Response website (http://earthdata.nasa.gov/data/near-real-time-data/rapid-response/modis-subsets). False color images combining Bands 7 (mid infrared), 2 (near infrared) and 1 (red) were analyzed as this band combination adequately differentiates water, soil and vegetation (Eyton, 2003). Water appears as false-color blue in this band combination, with light blue corresponding to shallow water (with light-colored soil visible underneath) and dark blue corresponding to water deeper than approximately 0.3 m in the case of the Cienega. We prepared a mask of the Santa Clara Slough area encompassing 36,000 ha, and used a supervised classification program in ERDAS software (ERDAS Imagine, Inc., Atlanta, GE) to divide the images into four classes, representing dry soil, wet soil, Water 1 (approximately 0.15–0.3 m or deeper) and Water 2 (0–0.15 m deep). Training sites were selected on images based on visual inspection of images and knowledge of water depths from ground and aerial surveys, and a signature file was developed that was then applied to all images analyzed.

## 3. Results

### 3.1. *Inflows, outflows, salinities and model validation during the reference period*

Measured inflow volumes and calculated outflows based on Eqs. (3) and (4) (MODIS ET estimates) are in Fig. 4A, and measured inflow salinities and wetland salinities measured at 22 stations are in Fig. 4B. Inflow volumes and salinities tended to be variable over the study period, with some months in which inflows were reduced due to low flows in the MODE canal, and periods of increased inflow salinity in summer, 2010 due to operation of the YDP. Salinities at the 22 stations ranged from 2.4 to 12 g $\mathrm{L^{-1}}$ TDS over the study. ET can also be estimated by Eqs. (1) and (2) by mass balance of salts and inflows (Glenn et al., 2012). Over the 33 month period in

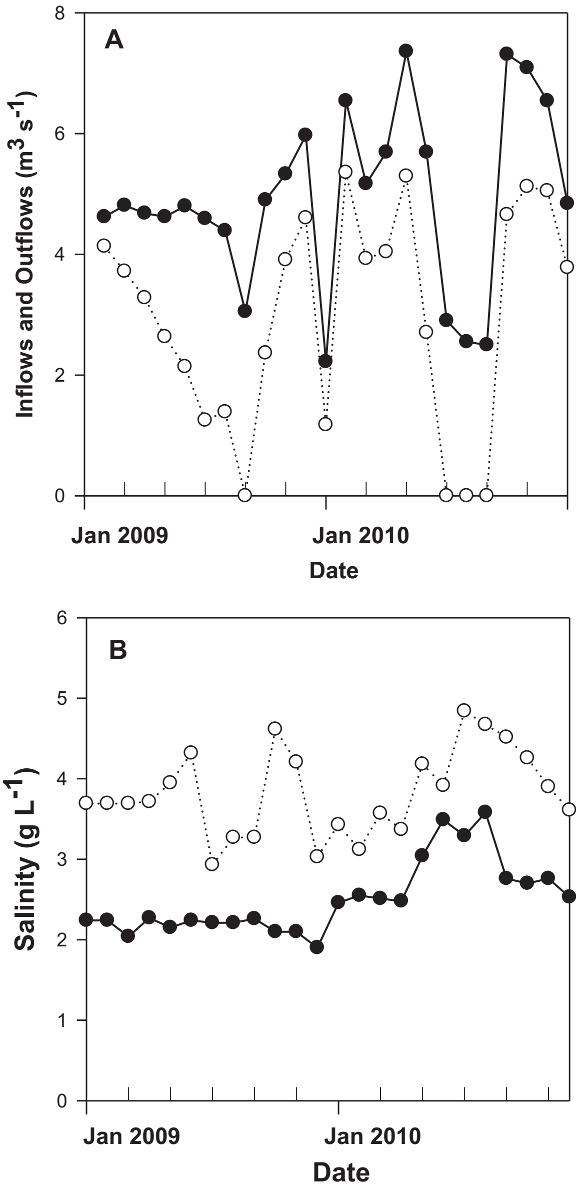

**Fig. 4.** Baseline data used in constructing models. (A) Measured inflows (closed circles) and calculated outflows based on ET (open circles). (B) Measured inflow salinity (closed circles) and mean wetland salinity measured at 22 stations within the Cienega (open circles).

which inflows and salinities were monitored (2009–2011), mean inflow salinity was $2.62\,\mathrm{g\,L^{-1}}$ TDS and mean wetland salinity was $3.73\,\mathrm{g\,L^{-1}}$ TDS (Table 1), for a $\beta$ value of 0.70. Therefore the fraction of inflow water that was lost in annual ET was estimated as (1.0–0.7), or 0.30. From Table 1 inflows were $4.97\,\mathrm{m^3\,s^{-1}}$ and wetland area was 4913 ha, hence by Eq. (6) ET in $\mathrm{m^3\,m^{-2}\,month^{-1}}$ was:

$$\frac{4.97\,\mathrm{m^3\,s^{-1}}(60\,\mathrm{s\ min^{-1}}\times 60\,\mathrm{min\ h^{-1}}\times 24\,\mathrm{h\ d^{-1}}\times 30.5\,\mathrm{d\ month^{-1}})0.3}{49,130,000\,\mathrm{m^2}} = 0.080 \qquad (11)$$

Whereas mean ET by the MODIS method was $0.070\,\mathrm{m^3\,m^{-2}}$ month over the same period, 13% lower (difference not significant at $P < 0.05$) (Glenn et al., 2012).

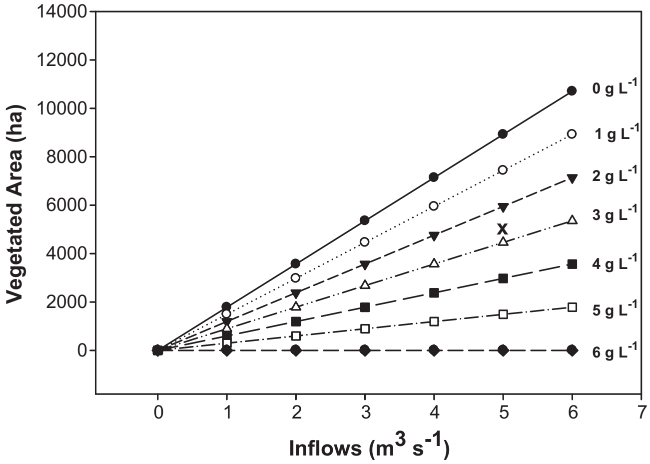

**Fig. 5.** Nomogram showing the projected area of *T. domingensis* in the Cienega as functions of volume and salinity of inflows. X indicates the present conditions in the Cienega.

Eq. (6) can also be used to estimate $E_{\mathrm{VEG}}$ during summer (June–August) and compared to MODIS $E_{\mathrm{VEG}}$ for the same period:

$$E_{\mathrm{VEG}} = \frac{\mathrm{SW}_{\mathrm{IN\text{-}Usable}}}{A_{\mathrm{VEG}}} \qquad (12)$$

June–August $\mathrm{SW_{IN}}$ in 2009 (before operation of the YDP) was $4.01\,\mathrm{m^3\,s^{-1}}$ and $\mathrm{SW}_{\mathrm{IN\text{-}Usable}}$ based on Eq. (6) was 0.56, and $A_{\mathrm{VEG}}$ was 4395, hence $E_{\mathrm{VEG}}$ was $0.137\,\mathrm{m^3\,m^{-2}\,month^{-1}}$. $E_{\mathrm{VEG}}$ by MODIS over the same period was $0.131\,\mathrm{m^3\,m^{-2}\,s^{-1}}$, 4.4% lower. Given the sources of error and uncertainty in both types of estimates, no adjustments to the model were made based on these comparisons.

### *3.2. Dependence of vegetated area on inflow volumes and salinities*

A nomogram relating the projected area of *T. domingensis* to inflow volume and salinities is in Fig. 5. Also shown on the graph is the area of vegetation under current conditions (2009–2010). As expected, at a given salinity the area of vegetation increases with increasing inflows, whereas at a given inflow volume, increasing salinity decreases the vegetated area due to the reduction in $\mathrm{SW}_{\mathrm{IN\text{-}Usable}}$ according to Eq. (6). Note that reductions in salinity can to some extent compensate for decreases in volumes; for example, if salinity is reduced to $2.0\,\mathrm{g\,L^{-1}}$ TDS, the volume of inflows could be reduced from the present $4.97\,\mathrm{m^3\,s^{-1}}$ to $4.0\,\mathrm{m^3\,s^{-1}}$ while maintaining the same area of *T. domingensis*. Conversely, if salinity is increased to $4\,\mathrm{g\,L^{-1}}$ TDS, increasing the inflow rate to $6\,\mathrm{g\,L^{-1}}$ TDS would partially compensate for the increase in salinity, but vegetated area would still decrease to approximately 3500 ha. Thus, by this model salinity appears to be a major determinant of the area of *T. domingensis* in the Cienega.

### *3.3. Dependence of outflow rates on inflow volumes and salinities*

Fig. 6 shows modeled monthly outflow volumes at three inflow rates and three salinities. Outflow volume as expected is highest during the winter, and is highly dependent on inflow rate but not on salinity. This is because *T. domingensis* is dormant in winter and $E_{\mathrm{VEG}}$ is very low, and about 90% of inflows exit into the Santa Clara

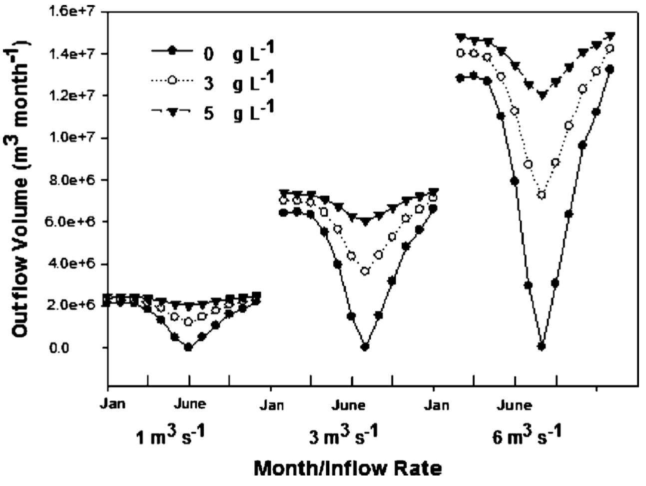

**Fig. 6.** Monthly projections of outflow volumes as functions of inflow volumes and salinities in the Cienega.

Slough. On the other hand, in summer outflows are lower than in winter due to increased ET, but outflow volume increases in response to salinity because $E_{\mathrm{VEG}}$ is constrained by salinity. When $C_{\mathrm{IN}}$ is 5 g L$^{-1}$ TDS, about 80% of inflow water exits to the Santa Clara Slough in summer, whereas all the water is consumed at $C_{\mathrm{IN}}$ of 0 g L$^{-1}$ TDS.

### 3.4. *Effect of outflows on surface area of water in the Santa Clara Slough*

Modeling of the pool area in the Santa Clara Slough indicated that outflows from 2009 to 2010 could sustain a peak pool area of about 5000 ha in winter, decreasing to near zero in summer, due to lower outflow volumes from the Cienega and higher rates of $E_{\mathrm{WATER}}$ in summer (Fig. 7A). Based on data in Figs. 6 and 7A, projections of winter and summer pool areas due to Cienega outflows at three inflow volumes and salinities are in Fig. 7B. Winter pool areas are mainly dependent on inflow volumes, as expected. However, summer pool areas are also dependent on salinity, with an inflow of 5 g L$^{-1}$ TDS supporting a large pool area, and a inflow of 0 g L$^{-1}$ TDS supporting near-zero pool area regardless of inflow volume. This is because the model assumes that $A_{\mathrm{VEG}}$ will expand to consume nearly all of the inflows in summer, because $SW_{\mathrm{IN\text{-}Usable}}$ is 1.0 at 0 g L$^{-1}$ TDS. This is a reasonable assumption because the vegetated area can expand to the south and along the western perimeter of the Cienega to use all available water.

January and June water surface areas determined by MODIS imagery for 2009–2011 are illustrated in Fig. 8 and summary statistics are in Table 3. The images were selected during neap tide conditions when contributions from recent tidal flooding were considered to be minimal. In winter, observed pool areas were about 14,400 ha, of which 50% was in the deeper Water 1 class, whereas summer pool area was only 2500 ha, consisting mostly of the shallow Water 2 class. For comparison, peak pool area attributed to Cienega outflows based on model predictions were 6400 ha in winter and the summer minimum was 100 ha. Thus under current conditions outflow from the Cienega appears to contribute 44% to the area of standing water in the Santa Clara Slough in winter in the absence of recent tidal inflows. Pool areas immediately following high tides >5 m, occurring 6–8 times per year, are in Fig. 9. Pool areas are expanded, but in summer much of this water evaporates in the interval between flooding, and the contribution from the Cienega is near zero due to high ET.

**Table 3**
Surface area of water in the Santa Clara Slough, 2009–2011, in January and July under neap tide conditions, based on MODIS imagery. Number in parentheses are standard errors of means.

| Class | Winter | Summer |
|---|---|---|
| Pool area (ha) | | |
| Water 1 | 6906 (335) | 752 (502) |
| Water 2 | 7502 (1184) | 1757 (562) |
| Wet soil | 7888 (550) | 3881 (557) |
| Dry soil | 14,419 (1349) | 30,083 (1567) |

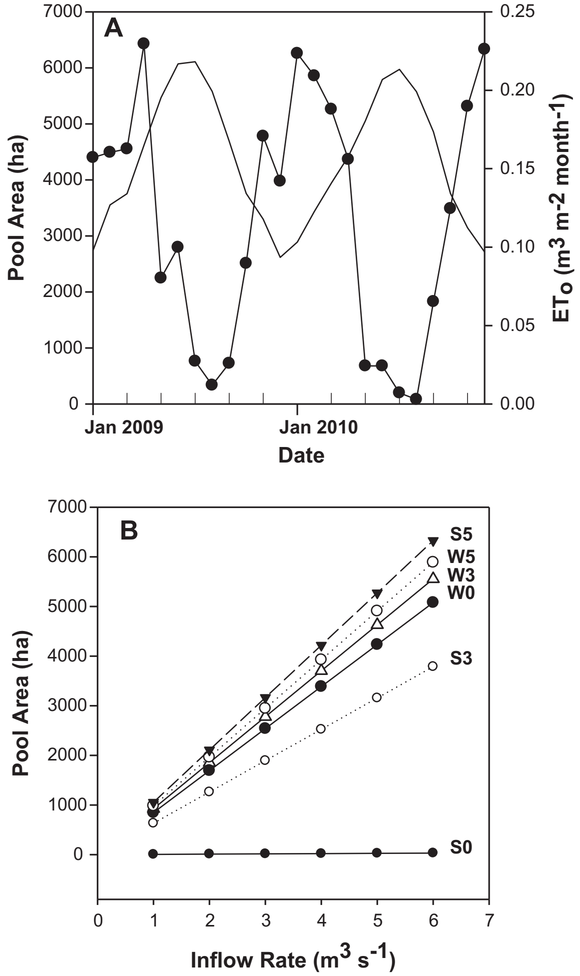

**Fig. 7.** (A) Projected pool area of the Santa Clara Slough based on outflows for the reference period, 2009–2010 (closed circles), compared to potential evapotranspiration (solid line). (B) Projections of summer (S) and winter (W) outflow pool area as functions of inflow volumes and salinities (0 = 0 g L$^{-1}$; 3 = 3 g L$^{-1}$; 5 = 5 g L$^{-1}$).

## 4. Discussion

### 4.1. *Factors controlling wetland dynamics*

The inflow rate, the salinity of the inflow and the ET rate interact to determine the area vegetated by *T. domingensis* and the amount of water that is potentially drained to the lower basin. Changes in $A_{\mathrm{VEG}}$ are assumed to occur over annual or longer time periods (Huckelbridge et al., 2010), whereas changes in $SW_{\mathrm{OUT}}$ are more dynamic, showing seasonal variability. When a range of salinity values is simulated there is a response to salinity in both the outflow volume and the area of the marsh. As salinity increases there is an increase in the estimated summer outflow due to salinity

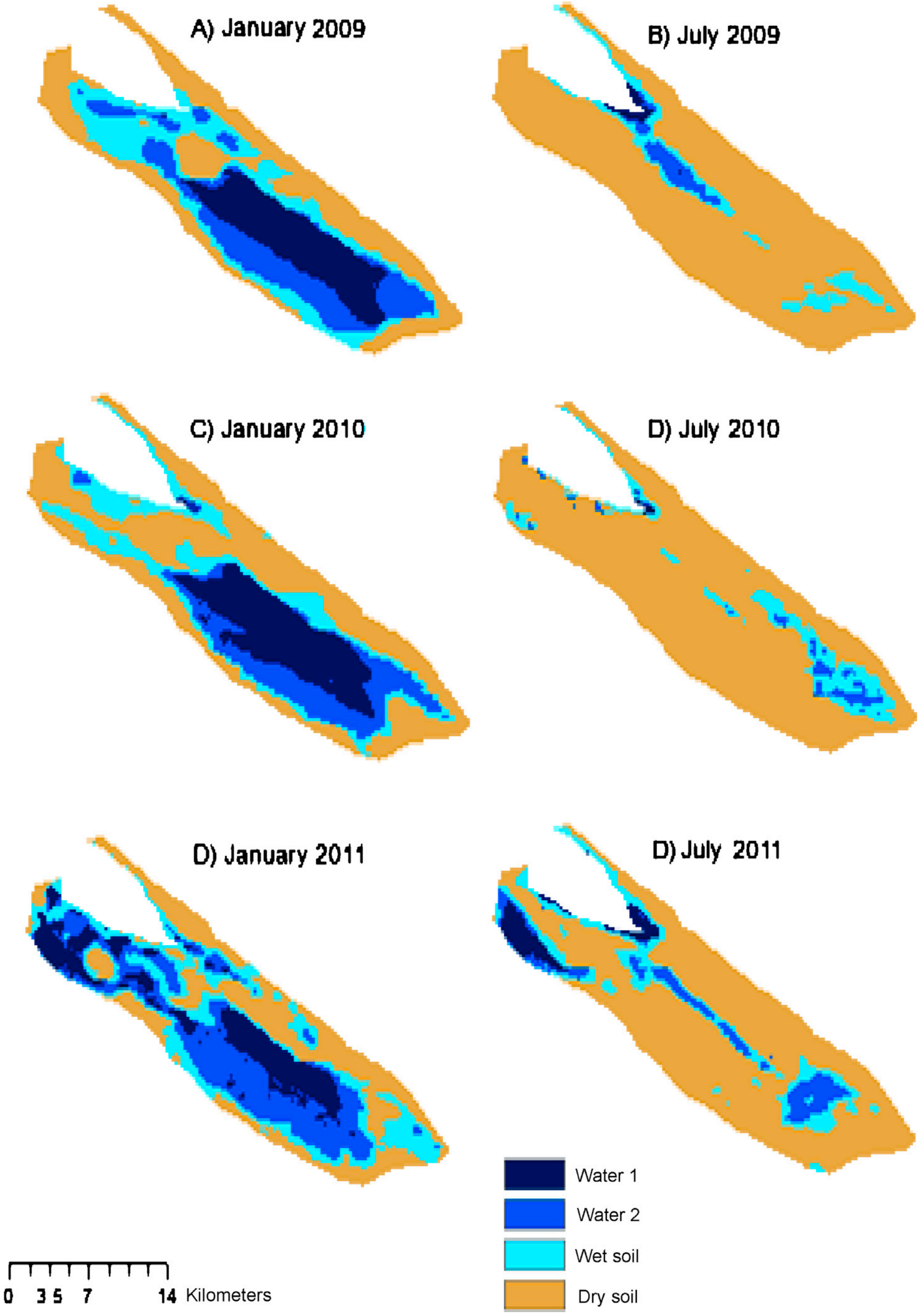

**Fig. 8.** January and July pool area in the Santa Clara Slough determined from MODIS imagery; images were obtained in neap tide conditions representing periods when overbank tidal flooding had not occurred for a month or longer.

constraints on *T. domingensis* $E_{VEG}$; this eventually leads to a contraction in $A_{VEG}$ over time. On the other hand, outflow volumes in winter are high in all salinity scenarios because *T. domingensis* is dormant and ET is low.

Huckelbridge et al. (2010) modeled the response of the vegetation of the Cienega to scenarios of water inflow and salinity integrating the interaction between wetland hydrology, mixing processes, salinity dynamics and vegetation, using a fixed percentage of outflow volume. They concluded the wetland is more sensitive to changes in salinity than to the volume of the inflow. Our approach, based on data collected 2009–2011 during the Cienega de Santa Clara Monitoring program (Greenberg and Schlatter, 2012), supports this conclusion. The sensitivity to salinity is due to the narrow salinity range over which *T. domingensis* can grow, with an upper salinity limit of 6 g $L^{-1}$ (Baeza et al., 2012).

Salts entering in a wetland can be stored in the water or soil, leave the system through the outflow or via plant uptake and harvest (Jia et al., 2011). In systems where the ratio between the outflow and the inflow approaches 0 the accumulation of salts will increase to high levels. An example of an anthropogenic wetland that accumulated salts and toxic elements due to lack of outflow is Kesterson National Wildlife Refuge in the San Joaquin Valley in California (Wu, 2004). Selenium present in the agricultural return flows that fed the wetland accumulated to toxic levels and the wetland had to be closed. Rather than being an isolated case, Lemly (1994) estimated that about half of wetlands receiving agricultural

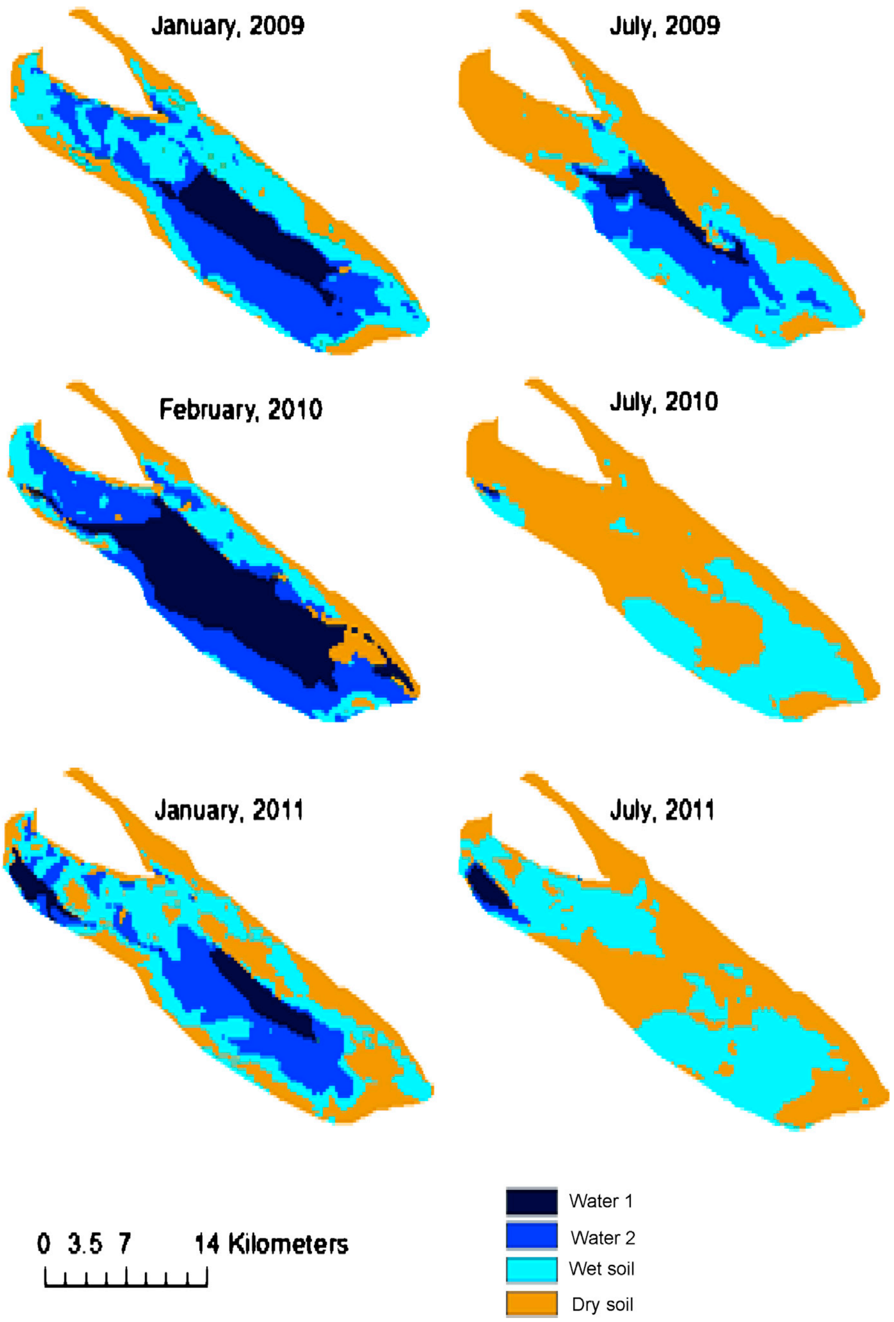

**Fig. 9.** January/February and July pool area in the Santa Clara Slough determined from MODIS imagery; images were obtained for dates following 5.2 m or higher tides that produced overbank flooding into the slough.

return flows experience accumulation of salts and toxic elements over time due to inadequate flushing (see also Jia et al., 2011). Typically, drain water follows a seasonal pattern corresponding to the cropping cycle in the agricultural district in which it is generated. By contrast, MODE water is delivered at a relatively constant rate throughout the year (Greenberg and Schlatter, 2012; Mexicano et al., 2013), and the Cienega has an outflow/inflow ratio close to 1 during winter months and an annual ratio of 0.7. This high annual outflow/inflow ratio appears to be functioning to prevent salt accumulation in the Cienega over time (Mexicano et al., 2013). Excess salts from the Cienega flow into the Santa Clara Slough, which is periodically flushed by tides, although it also functions as an evaporation basin, with large amounts of salt crystals visible on the soil between flood events. Hence, the Cienega is an open wetland system discharging into a partially open evaporation basin that is naturally hypersaline.

### 4.2. Operating scenarios for the YDP

The YDP has an intake capacity of 4.22 $m^3 s^{-1}$, and at full operation would produce 3.16 $m^3 s^{-1}$ of desalted water and 1.06 $m^3 s^{-1}$ of brine effluent containing 8–11 $g L^{-1}$ TDS depending on the salinity in the inflow water (Leitz and Ewoldsen, 1977; Lohman, 2003). Flows in the MODE averaged 4.30 $m^3 s^{-1}$ (SD = 0.46) and salinity averaged 2.59 $g L^{-1}$ TDS (SD = 0.32) from 1995 to 2010, hence nearly the full volume of MODE water could be diverted to the YDP. Several operating scenarios have been proposed to protect the Cienega ecosystem while operating the YDP to provide desalted water for

**Table 4**
Projections of *Typha domingensis* cover and area of water in the Santa Clara Slough attributable to Cienega outflows under different operating scenarios of the Yuma Desalination Plant.

| YDP operating scenario | Inflow volume to Cienega ($m^3 m^{-2} s^{-1}$) | Inflow salinity to Cienega ($g L^{-1}$ TDS) | Area *T. domingensis* (ha) | Summer outflow pool (ha) | Winter outflow pool (ha) |
|---|---|---|---|---|---|
| Full capacity | 1.06 | 10.3 | 0 | 1320 | 1320 |
| One-third capacity, brine placed in MODE | 3.16 | 3.46 | 2097 | 2400 | 2970 |
| One-third capacity, brine not placed in MODE | 2.81 | 2.59 | 2944 | 1460 | 2600 |
| No operation of YDP | 4.22 | 2.59 | 4395 | 2200 | 3900 |
| One-third capacity, brine not placed in MODE, replacement water of 1 g $L^{-1}$ TDS added | 4.22 | 2.19 | 5074 | 1947 | 3850 |

human use (Blank, 2007). Based on the models developed here, we evaluated four possible scenarios (Table 4). We took as the initial conditions the current inflow rates and salinities, and projected new scenarios to eventual equilibrium conditions. These included full operation of the YDP; operation at 1/3 capacity with placement of YDP brine in the MODE canal for delivery to the Cienega; operation at 1/3 capacity without placement of brine in the MODE canal; and operation at 1/3 capacity without placement of brine in the MODE and with replacement water from other sources provided with 2 g $L^{-1}$ TDS. The third and fourth scenarios would require an alternate method of disposing of the brine.

Table 4 shows that any reduction in inflow volume will proportionately reduce the area of *T. domingensis*, as expected. Salinity also decreases the vegetated area, but because there is an upper limit of 6 g $L^{-1}$ TDS for support of *T. domingensis*, even a moderate rise in salinity has a large impact on vegetated area. This is seen in the two operating scenarios at one-third capacity; in the first, when the effluent brine is placed back in the MODE, salinity increases by 0.87 g $L^{-1}$ TDS, resulting in a decrease in vegetated area of 847 ha compared to the scenario in which brine is disposed of elsewhere. On the other hand, sources of less saline water from the U.S. and Mexico have been proposed as replacement water, which could support the Cienega but are not suitable for desalting (e.g., treated sewage effluent, containing about 1 g $L^{-1}$ TDS). The fourth scenario shows that such water could actually increase the vegetated area in the Cienega.

### 4.3. *Model potential errors and limitations*

The models have two main sources of error and uncertainty. The first source is due to errors inherent in measurements of inflows and salinities and estimates of $E_{VEG}$ and $E_{WATER}$ by MODIS imagery and meteorological data. Despite the apparent good agreement between ET estimated by MODIS and by salinity measurements, both remote sensing and ground methods for estimating wide-area ET in wetlands have errors on the order of 20–30% (Kalma et al., 2008; Glenn et al., 2011). A detailed comparison of ET estimates by MODIS and mass-balance methods for the Cienega are in Glenn et al. (2012), and they differed by 13%. Hence the error in projected vegetated area in different operating scenarios is likely <15%. Greater error is likely associated with the estimates of the contribution of Cienega outflows to the surface area of water in the Santa Clara Slough, because outflows were not measured directly, and the topology of the receiving basin is poorly known. Errors in estimating the mean depth of the Santa Clara Slough could be as great as 50%, for example. It can be concluded that Cienega outflows probably make a significant contribution to the surface area of water in the slough, but the exact magnitude of this contribution cannot be estimated based on the relatively coarse approximations in the present model.

The second source of error and uncertainty is the validity of the assumptions built into the models, which determines how well they predict future conditions if inflow volumes and salinities to the Cienega are altered. The predictions of vegetated area depend on how well Eqs. (6) and (7) describe the relationship between $A_{VEG}$ and $C_{IN}$. Dudley et al. (2008) found that while $E_{VEG}$ of crop plants might decrease on a rate basis due to increased salinity, the final annual yield and crop water use could still be predicted from Eq. (6), in which the limiting factor over a growing season is the total amount of usable water available. Lowered rates of $E_{VEG}$ were compensated by slightly longer crop cycles in their field experiments. We assume similar considerations apply to the Cienega. In support, June–August values of salinity in the Cienega are in the range of 5–8 g $L^{-1}$ near the discharge points (Greenberg and Schlatter, 2012), similar to the value of 6 g $L^{-1}$ assigned to $C_{Threshold}$ in Eq. (6), indicating the vegetation is consuming the usable fraction of water in summer. However, there were insufficient reference data on which to test the full range of predictions modeled here, because inflow volumes and salinities have been relatively constant since creation of the Cienega in 1977, and interruptions in flow have been temporary. At higher salinities, it is not certain that the Cienega would remain a *Typha* marsh since other emergent species already present in the Cienega have higher salt tolerance and could at least partially replace *T. domingensis* if salinity increases. These include *Schoenoplectus americanus*, *Schoenoplectus maritimus* and *P. australis* (Mexicano et al., 2013). Hence, the models likely provide a reasonable approximation of the response of *T. domingensis* to altered inflows, but the eventual species composition of the marsh under altered inflows is unknown.

### 4.4. *Implications for management*

The results suggest some points that should be considered in designing an operating protocol for the YDP while preserving ecological functions in the Cienega and Santa Clara Slough:

- The area of *T. domingensis* is directly determined by the volume and salinity of inflows during the April–October growing season, and reductions in flows or increases in salinity will reduce the area of *T. domingensis*.
- Salinity is especially important in determining the area of *T. domingensis* due to its relatively low $C_{Threshold}$; therefore, disposing of YDP brine in the Cienega would appear to be especially detrimental to the marsh.
- Conversely, sources of replacement water with lower salinity than MODE water could enhance the area of *T. domingensis*.
- High outflow values in winter contribute to the area of shorebird habitat in the Santa Clara Slough and help maintain the salt balance in the Cienega by flushing salts accumulated in summer into the slough.

- High outflow volumes also prevent the accumulation of toxic elements such as boron and selenium to levels of concern (Greenberg and Schlatter, 2012).
- Reduction in size or fragmentation of coastal marshes generally reduces species abundance and diversity in the marsh (e.g., Craig, 2008; Guadagnin et al., 2009). Given the already much diminished wetland area in the delta, preserving the present area of the Cienega and Santa Clara Slough is important to maintaining avian habitat value in the delta.
- Stability of the Cienega de Santa Clara ecosystem appears to be sustainable over time due to its connection to the Santa Clara Slough evaporation basin and occasional connection to the sea at high tides.

Unlike some other anthropogenic wetlands supported by agricultural drain water (e.g., Lemly, 1994; Wu, 2004), the Cienega represents a success story that has maintained high-quality wildlife habitat for over 30 years. In summary, its stability can be attributed mainly to the high volume of winter outflows that keeps salts and toxic elements in balance, and its connection to the sea, which makes it an open rather than closed wetland system. Future management scenarios should be designed to preserve and enhance these attributes.

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