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An online, peer-reviewed journal
published in cooperation with the
Texas Water Resources Institute

Texas Water Journal

Volume 10 Number 1 | 2019

Texas Water Journal

Volume 10, Number 1
2019
ISSN 2160-5319

texaswaterjournal.org

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Texas Water Resources Institute
Texas Water Journal
Volume 10, Number 1, June 7, 2019
Pages 46-59

A Tool for Rapid Assessment of Hydrological Connectivity Patterns in Texas Coastal Wetlands: Linkages between Tidal Creeks and Coastal Ponds

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Abstract: Coastal salt marshes are heterogeneous, spatially complex ecosystems. The degree of hydrological connectivity in these systems can be a significant driver in the flux of energy, organisms, and nutrients across the marsh landscape. In tidally driven systems, the frequency and magnitude of hydrological connection events results in the creation of a matrix of intermittently connected coastal wetland habitats, some of which may be hydrologically isolated or partially drained at any given time. Previous approaches to understanding landscape-level hydrologic connectivity patterns have required either intensive long-term monitoring or spatially explicit modeling. In this paper, we first describe a 13-month field study in the Guadalupe Estuary of the Texas Gulf Coast that linked hydrological connectivity patterns between a saltwater pond to water levels in an adjacent tidal creek and nearby San Antonio Bay. We next describe the integration of these field data with high-resolution digital elevation models and environmental parameters to develop a spatially explicit model that is a Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod (SLOSH). We evaluated the ability of SLOSH to simulate trends in landscape-level patterns of hydrological connectivity between a tidal creek and an inland marsh pond. Magnitude and periodicity of simulated and observed water-level fluctuations in the pond were similar. Highest creek water levels, resulting in high frequency and duration of hydrological connectivity with the pond, corresponded with the highest bay water levels, which occurred during September and October. Lowest creek water levels, resulting in low frequency and duration of hydrological connectivity, corresponded with the lowest bay water levels, which occurred during December through February. By simulating the pulsing structure of salt marsh hydrology, SLOSH creates the foundation on which to assess how additional drivers (precipitation, wind, freshwater inflows, etc.) can influence coastal marsh hydrology and overall ecology.

Keywords: Aransas National Wildlife Refuge, freshwater inflows, hydroperiod, saltwater ponds, water level, whooping crane (*Grus americana*)

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Citation: Swannack TM, Wozniak JR, Grant WE, Davis SE III. 2019. A tool for rapid assessment of hydrological connectivity patterns in Texas coastal wetlands: linkages between tidal creeks and coastal ponds. Texas Water Journal. 10(1):46-59. Available from: https://doi.org/10.21423/twj.v10i1.7073.

Terms used in paper

Acronyms	Descriptive name
ANWR	Aransas National Wildlife Refuge
BR_t	mean daily tidal creek water levels
BR	Boat Ramp
cm	centimeters
DEM	Digital Elevation Models
ET	evapotranspiration
ft	feet
GIW	Gulf Intracoastal Waterway
GIS	geographic information system
ha	hectares
in	inches
km^3	cubic kilometers
lidar	Light Detection and Ranging
$MaxT_t$	daily maximum temperatures
m	meters
mm	millimeters
$MinT_t$	daily minimum temperatures
NAVD88	North American Vertical Datum of 1988
Ra	mean daily solar radiation (MJ $m^{-2}day^{-2}$)
Sd_t	mean daily water levels at the Seadrift gage in San Antonio Bay
SLOSH	Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod

INTRODUCTION

Coastal salt marshes are heterogeneous, spatially complex landscapes comprised of a wide variety of habitat types. The degree of hydrological connectivity across the coastal marsh landscape can be a significant driver in the formation and maintenance of the ecological resources found in these habitats. Environmental factors including mean sea level, tidal cycles, and wind velocity and direction can directly influence hydrological connectivity in aquatic systems, specifically affecting water column flushing rates, salinity, nutrient supply, species diversity, and primary production (Odum et al. 1995; Bornette et al. 1998; Ward et al. 1999; Ahearn et al. 2006; Leibowitz and Vining 2003; Miller et al. 2009; Wilcox et al. 2011). With increased pressures on coastal ecosystems (e.g., storm effects, sea level rise, human impacts), it is critical to understand how these variables work in concert to influence spatial and temporal patterns of hydrological connectivity across the coastal salt marsh landscape.

The degree of hydrological connectivity plays an important role in determining the flux of energy, material, and nutrients across the salt marsh landscape. In many estuarine systems, much of the nutrient load is delivered to the salt marsh via freshwater inflow originating from upstream in the watershed. However, in marshes located farther from the mouth of the estuary, at increased distances from tidal creeks, or occurring at higher elevations in relation to mean water levels, the degree of hydrological connectivity can be the regulating factor that dictates ecosystem productivity by allowing the exchange of energy, nutrients, and organisms with the marine environment (Odum et al. 1995; Pringle 2001). In tidally driven systems, there is a clear hydrological disconnect between near tidal creek habitats and more inland marsh habitats (Ragan and Wozniak 2019). During periods of low water level (e.g., low tide), water actively drains from habitats in close proximity to tidal creeks, whereas inland marsh habitats often experience delayed or incomplete drainage due to micro-elevational changes in marsh topography, which leads to fewer points of hydrological connection and subsequent shifts in marsh water quality (Valiela et al. 1978; Prado et al. 2017).

In highly heterogeneous coastal marsh settings, there are multiple connection points, which are distributed across the landscape and sometimes independent of lateral distance from tidal waters. This results in a matrix of intermittently connected ponds—relatively small patches of inundated marsh—each often operating independently from the others that may be drawn down or completely drained during periods of low tides, low rainfall, and increased evapotranspiration (ET). These dry-down phases can persist for extended periods of time (several days to weeks) and often lead to hypersaline conditions, hydrologic isolation, barriers to the movement of aquatic organisms into and out of inland marsh ponds (Day et al. 2012; Ragan and Wozniak 2019), and the reduction of primary productivity (Zedler et al. 1980). Understanding connectivity in micro-tidal estuaries is particularly important because these patterns do not relate directly to lunar tidal cycles and are a result of interactions of a relatively flat environment and other drivers of water level fluctuation (e.g., wind, storm surge, fortnightly tides, etc.).

For salt marsh systems that provide critical ecosystem services (e.g., flood risk reduction) or contain endangered species, it is important for natural resource managers to understand how different management actions permeate through their system. However, the complexity of inland marsh hydro-connectivity patterns makes developing management strategies challenging, particularly because few predictive models have been generated for the natural resource management community. Computational models that predict marsh dynamics often do not include inland ponds (Park et al. 1989; Moorhead and Brinson 1995; Nicholls 2004; Poulter and Halpin 2008); nor do they involve complex analytical solutions that explore the geophysical properties of marshes that link to the ecology (Fagherazzi et al. 2012; Fagherazzi and Furbish 2001; Mariotti and Fagherazzi 2010). High-resolution Light Detection and Ranging (lidar) data, which is capable of distinguishing the fine-scaled topographic features affecting overland flow (Lindsay 2006), allows for the development of a rapid assessment modeling tool that simulates the seasonal and year-to-year dynamics of fine-scale water level patterns within salt marsh ecosystems.

In this paper, we describe a 13-month field study that linked hydrological connectivity patterns within a salt marsh in the Guadalupe Estuary of the Texas Gulf Coast to water levels in the adjacent San Antonio Bay. We next describe integration of these field data into a spatially explicit model that simulates hydrological connectivity at a fine spatial scale in salt marsh ecosystems. The ability of the model to simulate the trends in landscape-level patterns of hydrological connectivity was assessed by comparing simulated connectivity patterns to connectivity patterns observed in the field between a tidal creek and an inland marsh pond. By simulating the pulsing structure of salt marsh hydrology, the simulation creates the foundation on which to assess how additional drivers (precipitation, wind, freshwater inflows, etc.) can influence the distribution of nutrients, abundance of organisms, and overall coastal marsh ecology.

METHODS

Study site

The Coastal Bend region of Texas includes numerous bays and estuaries that are ecologically and economically important. One such system, the Guadalupe Estuary, which includes San Antonio Bay, is a shallow (1 meter [m] mean depth [3.28 feet {ft}]) lagoonal estuary (about 550 square kilometers [km^2] in area) located along the mid-Texas coast (Figure 1). The estuary is fed primarily by the combined discharge of the San Antonio and Guadalupe rivers and is separated from the Gulf of Mexico by Matagorda Island. Aransas National Wildlife Refuge (ANWR) occupies much of the Blackjack Peninsula that extends out into the estuary and contains nearly 2,800 hectares (ha) [6,918 acres] of salt marsh interspersed with tidal creeks, inland bays, and intermittently connected marsh ponds (Figure 2). The irregularly flooded salt marsh along the ANWR possesses a narrow fringe of *Spartina alterniflora Loisel.* (1–2 m [3.28–6.56 feet] wide) and inland habitats dominated by a mixed high-marsh vegetation community including *Distichlis spicata* L. Greene, *Lycium carolinianum* Walt., and *Salicornia virginica* L. (see Butzler and Davis 2006 for a detailed description of the vegetation community). The marsh and ponds undergo inundation and connection/disconnection at irregular intervals throughout the year, and the marsh ecosystem is characterized by compact poorly-drained mineral soils. Thus, different ponds vary in terms of water level, nutrient content, and benthic production as a result of their frequency and duration of connection to tidal waters (Miller et al. 2009).

The overall stability and production of the marsh food web is of critical importance as these marshes are the wintering habitat of the endangered whooping crane (*Grus americana*). Whooping cranes utilize the ANWR salt marsh from mid-October through mid-April, foraging primarily on Carolina wolfberry (*Lycium carolinianum* Walt.) and aquatic invertebrates (such as blue crabs [*Callinectes sapidus* Rathburn], fiddler crabs [*Uca* spp.], and clams [family Corbiculidae]). These aquatic invertebrates are readily found in the marsh ponds and are dispersed across the inland marsh landscape via hydrologic connection events (Hunt and Slack 1989; Butzler and Davis 2006; Miller et al. 2009).

This paper focuses on the Boat Ramp (BR) study site located on the Blackjack Peninsula of the ANWR (Figures 1 and 2). The BR site is comprised of an extensive tidal creek-open marsh-saltwater pond complex (Figure 2). The pond we focused

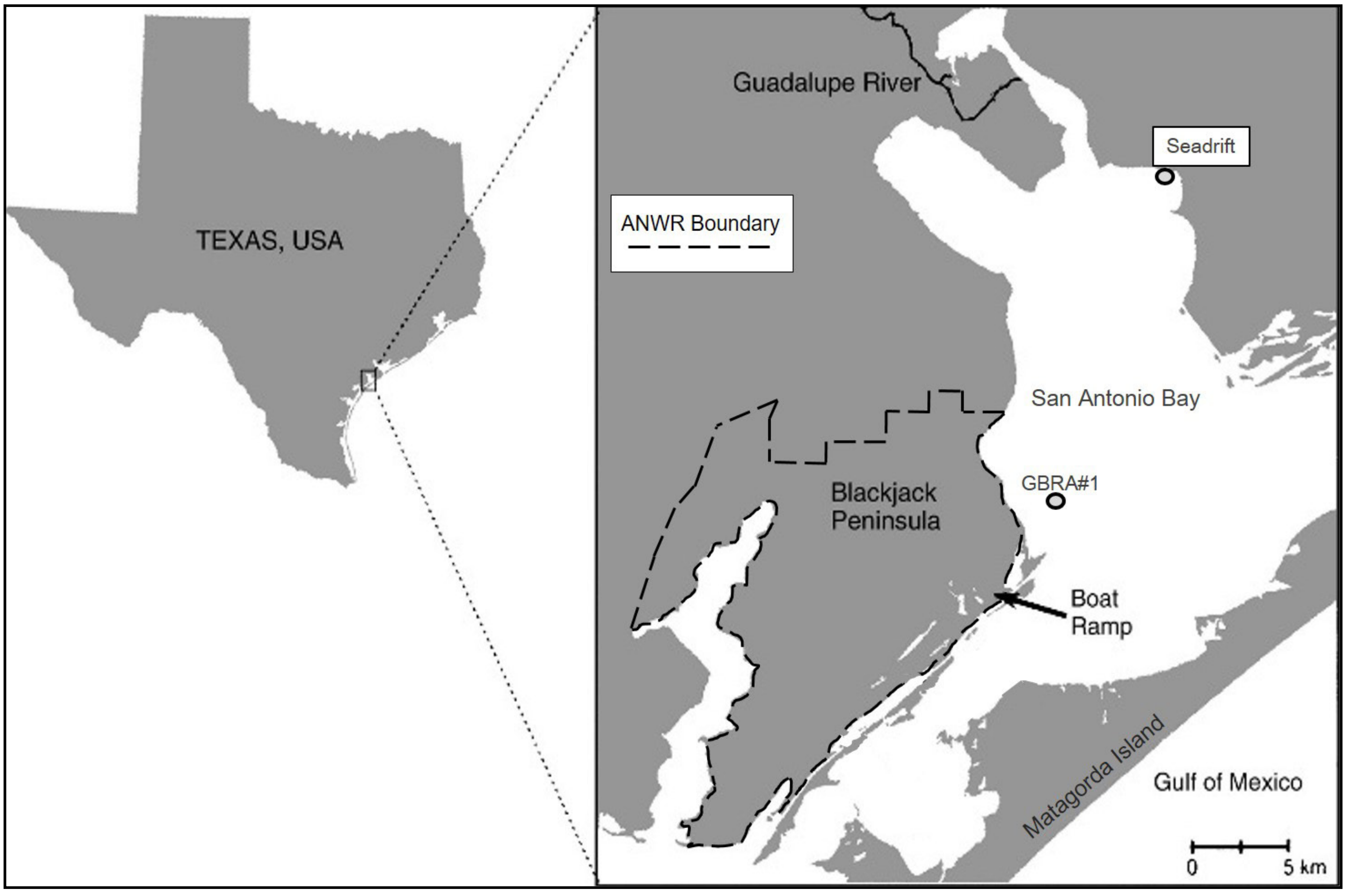

Figure 1. Map of the study system including the Guadalupe River, San Antonio Bay, and the Aransas National Wildlife Refuge (ANWR) located on the Blackjack Peninsula (boundary designated by the black dashed line). The locations of the coastal wetland research site, Boat Ramp (BR), at the ANWR and Seadrift water level monitoring station are also shown.

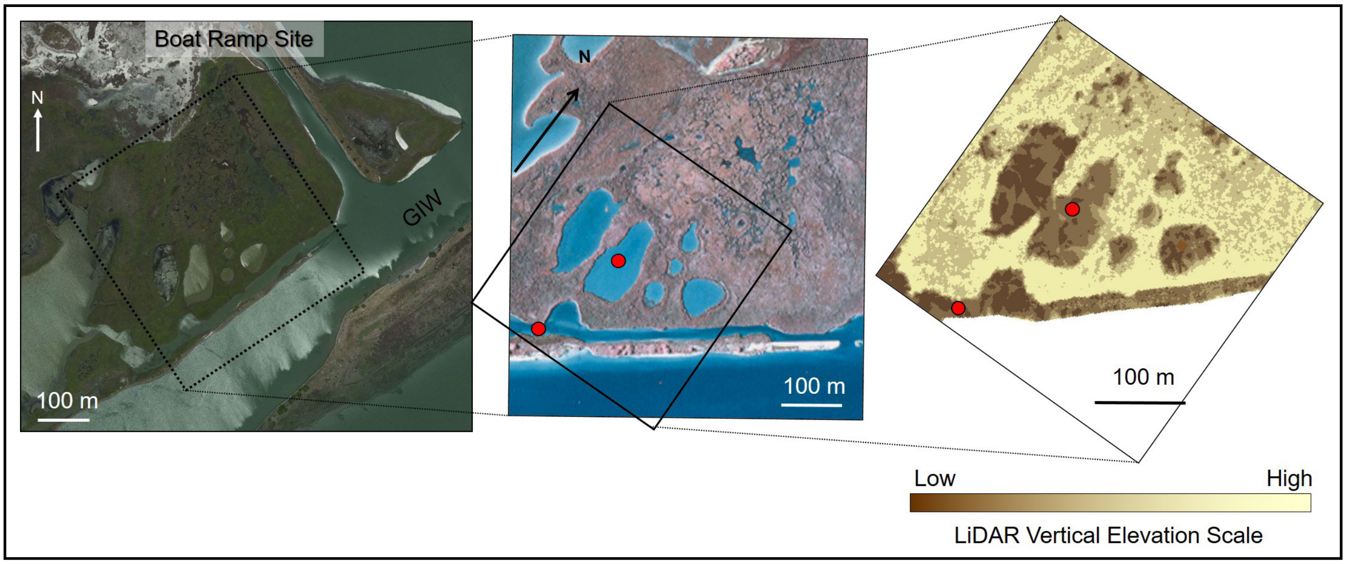

Figure 2. Left: Satellite images of Boat Ramp (BR) territory at the Aransas National Wildlife Refuge, Aransas, Texas. The box represents the approximate area chosen as the representative sample upon which Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod (SLOSH) was parameterized. Right: Lidar image of the BR territory on which SLOSH was parameterized. Green squares represent georeferenced location of water level gages used during the field studies. On the lidar image, the vertical elevation scale is shown by color with darker browns representing lower elevations and lighter tans representing higher elevations. The georeferenced locations of the tidal creek and pond water level gages are shown as red circles.

on is elliptical in shape (61 m x 137 m [200.13 ft x 449.48 ft]) and characterized by an intermittent hydrologic connection regime, becoming isolated (and at times completely dry) during periods of drought and connected with the other ponds and the greater marsh landscape during high water events. The BR tidal creek runs parallel to the Gulf Intracoastal Waterway (GIW) in a general northeast–southwest orientation. Compared to other tidal creeks along the Blackjack Peninsula, the BR tidal creek is closest to San Antonio Bay and the mouth of the Guadalupe River (approximately 26 km, or 16.2 miles to the north) and is in close proximity to the GIW (< 25 m [< 82.02 ft]). A study by Davis et al. (2009) indicated that water level fluctuations caused by barge-induced drawdown currents along the GIW were greater at the BR site compared with other ANWR tidal creeks and comparable to the diurnal tidal range (typically 10–15 cm [3.94–5.91 inches {in}]).

Simulation data sources and collection

Water level data loggers with built-in pressure sensors that compensate for changes in atmospheric pressure (accurate to +/- 0.1% of the range; Infinities USA) were placed in the tidal creek and in the nearby pond for a 13.5-month period between June 2003 and August 2004 (Figure 2). Water levels were recorded hourly, and each gage site was surveyed relative to benchmarks established within the marsh (described in detail in Miller et al. 2009). In order to determine if tidal creek water levels were influenced by bay water levels, we correlated mean daily tidal creek water levels with mean daily bay water levels, which we compiled from the Texas Coastal Ocean Observation Network water level gage data collected near Seadrift, Texas (TCOON).

Hourly tidal creek water levels during the study period were plotted and the hydrological connection point was defined as the point where the statistical relationship between tidal creek water levels and pond water levels were not statistically different from each other via comparing the slopes of the simulated and observed water levels using analysis of co-variance. Next, the tidal creek water level connection point was used to estimate the pond water level and the associated timing of connection events. Daily maximum and minimum air temperatures (°C) from the weather station at the ANWR (station ID 410305) for all dates between June 2003 and August 2004 were extracted (NCEI date). These data were used during the simulation to calculate ET rates for the inland marsh ponds. Daily solar extraterrestrial radiation was extracted from the Food and Agriculture Organization data tables (Allen et.al. 1998, Annex 2. Meteorological tables) for the latitude of the ANWR. Precipitation data were not considered because precipitation events did not alter pond water levels during the field study as the area was experiencing drought conditions.

We obtained georeferenced elevation data from lidar data of Calhoun and Aransas counties, Texas from the Texas Natural Resources Information System website (TNRIS 2019). Lidar were processed using standard procedures and projected in the North American Vertical Datum of 1988 (NAVD88) geodetic vertical datum. All geographic information system (GIS) file manipulations were done using ArcGIS v9.1.

Water level simulation model description

Based on the attributes of the BR study site and the location of the *in situ* water level loggers, we developed a grid-based, spatially explicit model that is a Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod (SLOSH). The model consists of two submodules: the first calculates the water level at which each cell in the grid is connected to the tidal creek; the second simulates a time series of water level changes over the landscape based on a regression equation that correlated the water level in San Antonio Bay (via the Seadrift, Texas gage station) with data from the BR tidal creek water level logger, solar radiation, air temperature, and the lidar data. The connection points calculated in submodule one are based solely on lidar elevations and are independent of the water level data. Similarly, observed pond water levels were not used in model parameterization and were used as the validation dataset to evaluate the ability of the model to simulate the timing of surface water connections with the BR tidal creek. The details of this process are described in the following sections and a comprehensive conceptual diagram that describes the specific flow of model/coding operations of SLOSH is presented in Figure 3.

Marsh topography

To accurately represent marsh topography in the simulation model, we created a grid of 47,607 cells (cell size: 1.4m^2 [15.07 ft^2], total area: 9.33 ha [23.05 acres]) that included the elevations extracted from the lidar layer and the georeferenced locations of the BR tidal creek and saltwater pond water gages (Figure 2). This grid was topographically and ecologically representative of the BR's salt marsh study site. This grid file containing georeferenced elevation was used as an input file for the simulation model, serving as the foundation for assessing water level fluctuation.

Model initialization

SLOSH is grid-based simulation package programmed in VB.NET (© Microsoft 2003). The simulation proceeds in two steps: (1) determine the tidal creek water level at which each cell is connected hydrologically to the tidal creek; and (2) simulate inland marsh pond hydrodynamics for a period of time defined by the user (the model runs on a daily time step by default

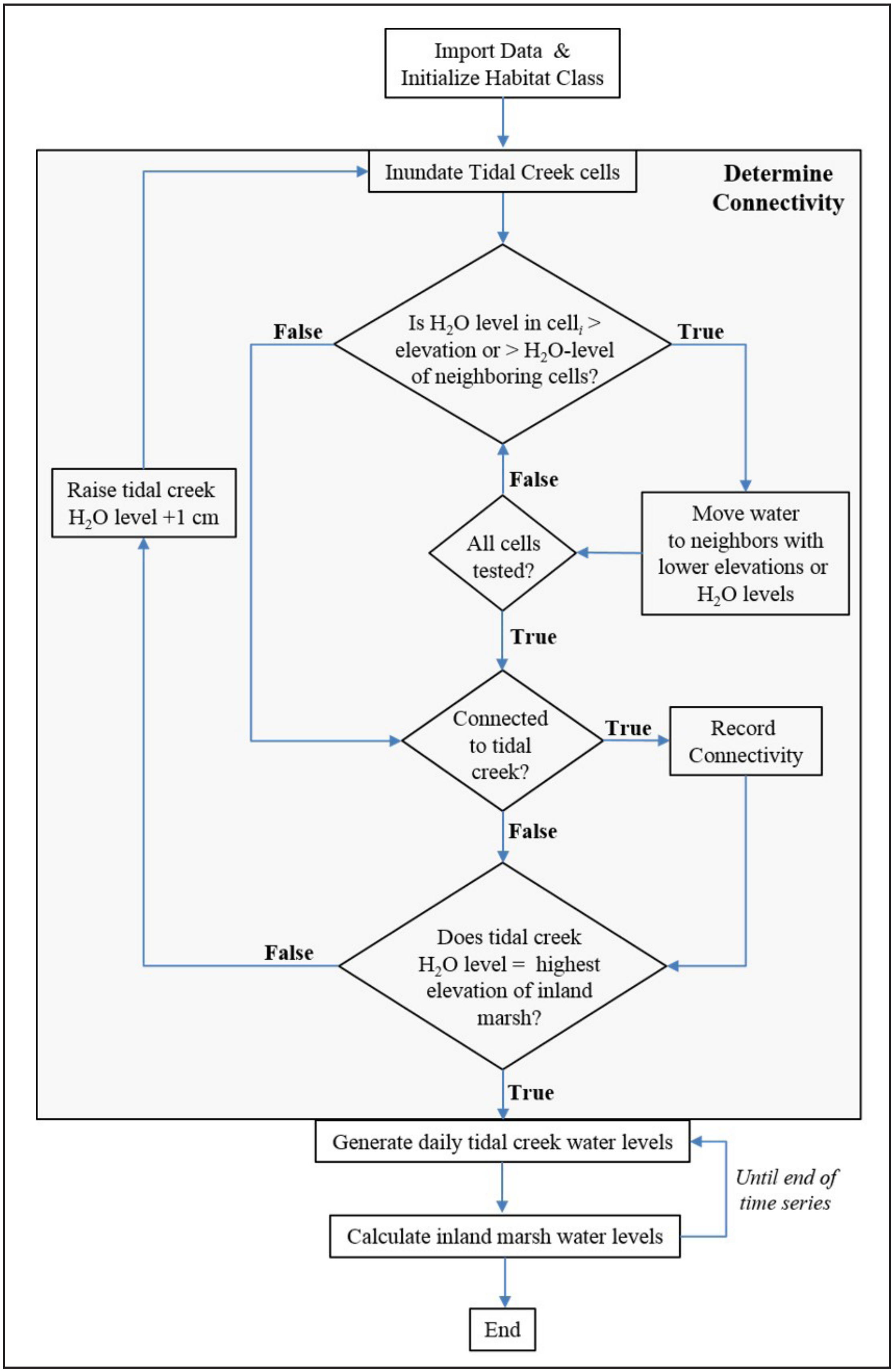

Figure 3. Flow diagram of model calculations. Rectangles indicate computations or data input/output. Diamonds indicate conditional statements. Gray box indicates the *determine connectivity* submodel.

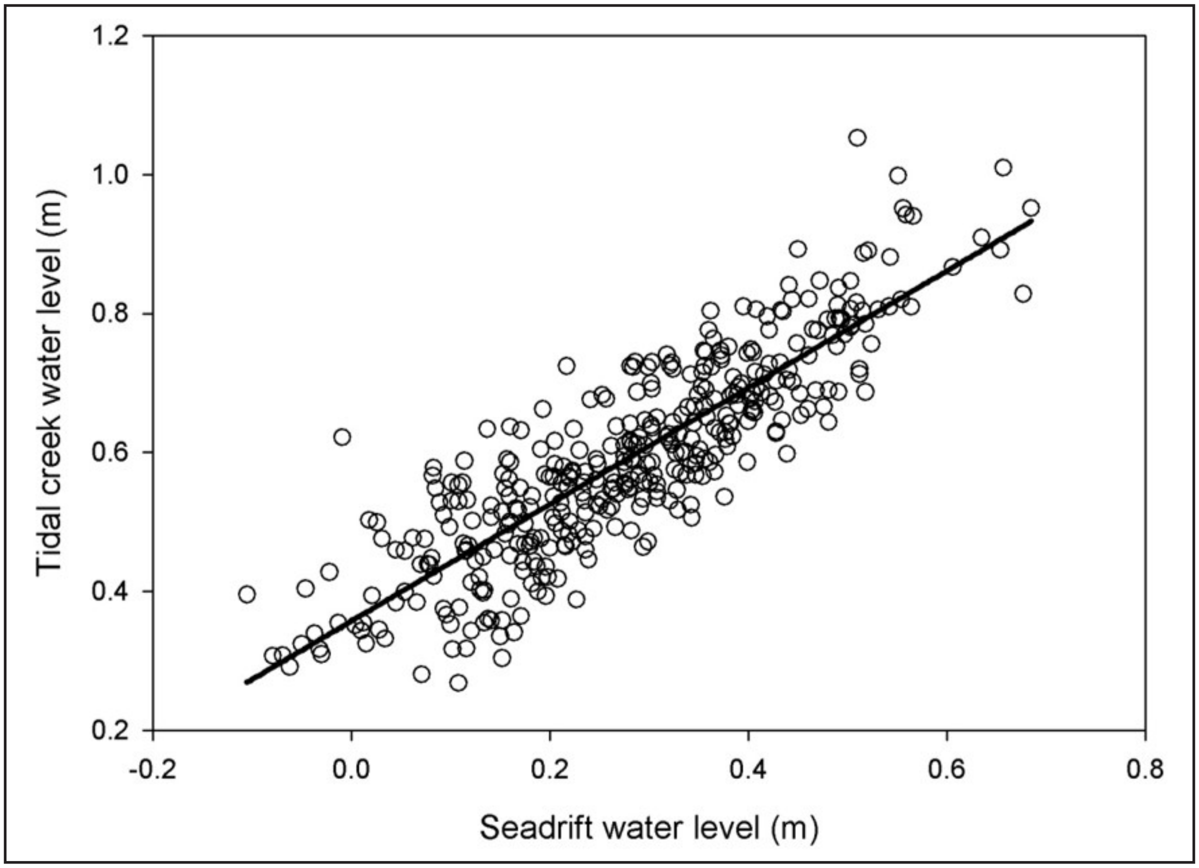

Figure 4. Correlation between mean daily water levels (meters above sea level, corrected for the NAVD88 vertical datum) calculated from water level data recorded at Seadrift (Sd_t) in San Antonio Bay (Figure 1) and mean daily water levels calculated from the hourly *in situ* data recorded at the gage in the tidal creek at the Boat Ramp study site (BR_t). Data shown are from 17 August 2003 to 24 June 2004.

but can be changed by the user). Model initialization begins with the parameterization of marsh topography (represented by grid cells inputted from a .csv file). Each grid cell is assigned its elevation value and XY coordinates, thus creating a virtual topography composed of the georeferenced cells. In addition to elevation and XY coordinates, each cell is initialized with the following three attributes: (1) current water level of the cell; (2) the BR tidal creek water level at which the cell's surface water connection to the tidal creek was established (calculated in the first step of the simulation); and (3) the concurrent water level in San Antonio Bay.

Determining hydrologic connectivity

We initialized the SLOSH with water only in those cells located within the GIW. We progressively flooded these cells by iteratively raising water levels within the initially flooded cells by 1 cm (0.39 in), then allowing the water to move into neighboring cells with lower elevations and/or water levels, until all changes in water levels within the system were < 0.1 cm (< 0.04 in). The current water level of each newly flooded cell was updated, and then the process was repeated until all the cells had been inundated across the marsh (see Figure 3 for a logic diagram of model flow). The tidal creek water level at which each cell was connected to the tidal creek was recorded (essentially, we created a lookup table that was our simulation referenced when processing tidal creek water levels) and was used as input data for the simulation of salt marsh hydroperiod. Connection levels of inland cells and the tidal creek water levels were determined and stored as an attribute of the grid cells. Specifying the surface water connection as an attribute of each cell, although computationally intensive, subsequently greatly reduced the time required to simulate the inundation regime associated with any given time series of water levels.

Simulating salt marsh hydroperiod

To initialize a simulation of salt marsh hydroperiod, we imported a time series of bay water levels from the Seadrift gage and used a linear correlation between mean daily tidal creek water levels (BR_t) and mean daily water levels at the Seadrift gage in San Antonio Bay (Sd_t) (Figure 4):

$$BR_t = 0.357 + 0.8399 * Sd_t, \ (r^2 = 0.745, \ n = 396) \qquad (1)$$

The correlation between tidal creek water levels and mean daily water ($r^2 = 0.745$) was strong, and we assumed that the predicted mean would best capture the general system trends (i.e., we did not incorporate error from Equation 1 into our simulation). We simulated inland marsh hydrodynamics by iterating through the time series of bay water levels, using Equation 1 to convert the values to BR_t and then using the water level connection point for each cell (defined in section 3) to determine if the cell was hydrologically connected to the tidal creek. If it was connected, then that cell was inundated. We assumed water loss was negligible while cells were hydrologically-connected to the tidal creek. During periods of disconnection, we represented water loss from each cell due to ET (ET_t, mm day^{-1}) by parameterizing the Hargreaves equation (Hargreaves et al. 1985):

$$ET_t = 0.0023 * (((MaxT_t + MinT_t) / 2) * ((MaxT_t - MinT_t)0.5))) * Ra \qquad (2)$$

where $MaxT_t$ and $MinT_t$ represent daily maximum and minimum temperatures (°C), respectively, and Ra represents mean daily solar radiation (MJ m^{-2}day^{-2}), based on the solar radiation and temperature data recorded near the study site. We used Ra values for the 15th of each month, which provide good estimates (<1.0% error) of Ra averaged over all the days within a month (Allen et al. 1998; Allen et al. 2005). ET was treated as a deterministic variable to capture general system trends. Future iterations of the model should include treating ET stochastically. We did not include water losses due to percolation of water into the marsh soils because coastal water tables are relatively high, and sandy clay soils, which are typical of the study site, have very low percolation rates (Rawls et al. 1992). We also did not include precipitation in water balance calculations, because precipitation events during the study period did not have a noticeable effect on the water balance in the marsh system relative to tidal inputs (Miller et al. 2009). However, precipitation can be incorporated into the model in future simulations of large rainfall events (hurricanes, etc.), which may result in increased precipitation-driven marsh flooding. We initialized SLOSH with a 10-year time series of values representing mean daily water levels in San Antonio Bay, mean daily solar radiation, and maximum and minimum air temperatures near the study site, from 1 January 1997 to 31 December 2007.

Simulation model verification and evaluation

We evaluated the ability of SLOSH to simulate the observed trends in surface water connections between the tidal creek and the pond by comparing simulated results to field data from a 303-day period during our field study (from 17 August 2003 to 24 June 2004). Observed pond water level data were not used in model parameterization so we could have an independent data source to verify model outputs. Field gages were not working for a 15-day period from 5 January 2004 to 19 January 2004, so simulated data representing that period were not included in the comparison. We verified that the model generated the observed temporal dynamics of mean daily water levels in the tidal creek. We compared (a) simulated to observed water levels in the marsh pond and (b) the simulated versus field-estimated tidal creek water level at which a surface water connection was established between the tidal creek and the pond. Connection points were recorded if the simulated marsh pond gage was hydrologically connected to the tidal creek. Hydrological connectivity between the simulated tidal creek and simulated marsh pond was determined using the same techniques that were used in the field.

RESULTS

Field results

Our field monitoring indicated that tidal flow from San Antonio Bay into the BR creek was the main factor leading to hydrologic connections driving inland pond water level. Daily high tides did not always lead to connection events between the creek and pond due to tides not breaching the dike of the tidal creek as well as micro-elevational changes across the marsh limiting water flow. In fact, seasonal and fortnightly tides accounted for much of the intra-annual variability in water level range (Figure 5a). Tidal creek water level was strongly correlated with water level at the Seadrift gage, located on the northeastern shore of San Antonio Bay (Figure 5, adj. $r^2 = 0.745$). A hydrological connection event occurred when the tidal creek water level was 0.7 m (2.30 ft.) and the pond water level was at least 0.37 m (1.21 ft; Figure 6). Based on this estimation, we observed 11 hydrological connections between the pond and tidal creek during the 13-month study (Figure 5b).

SLOSH verification and evaluation

Magnitude and periodicity of water level fluctuations in the tidal creek generated by Equation 1 reflected those recorded during the field study well, but water levels generally tended to be overestimated at higher tidal creek water levels (Figure 5a). Magnitude and periodicity of simulated and observed water level fluctuations in the pond were similar, but simulated pond water levels differed, on average, from observed pond water levels by 0.17 m (± 0.082 m) (Figure 5b). A hydrological connection occurred when the simulated tidal creek water level was 0.71 m (2.33 ft) and the pond water level was at least 0.57 m (1.87 ft; Figure 6). SLOSH generated 14 hydrological connections between the tidal creek and pond, which corresponded well temporally with the 11 connections observed in the field (Figure 5b). SLOSH captured all of the observed connection events but also simulated three additional events on 23

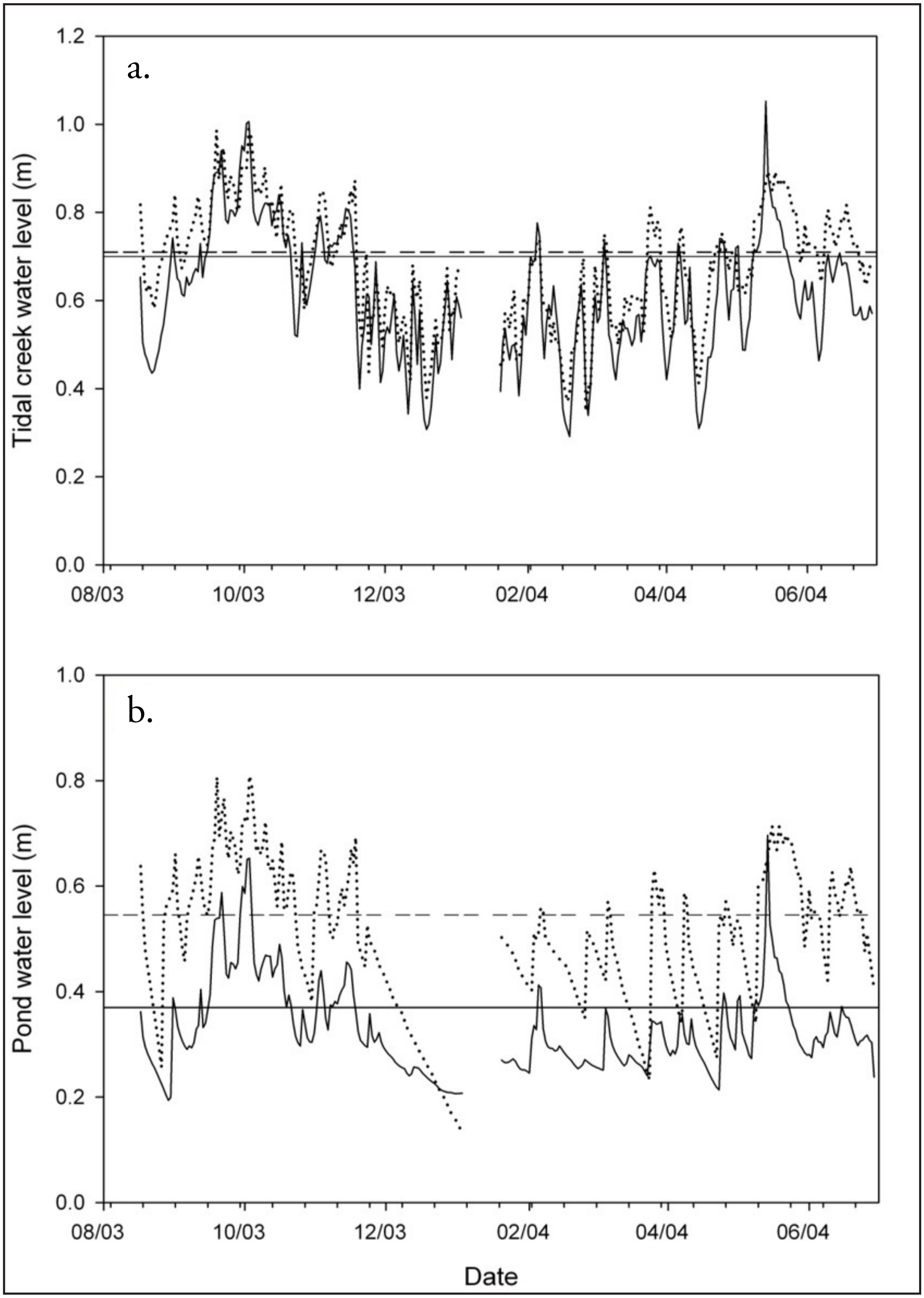

Figure 5. Observed and simulated temporal dynamics of mean daily water levels in (**a**) the tidal creek and (**b**) the marsh pond. Solid lines represent observed field data, and dotted lines represent simulated data from Simulation of Landscape-level Oscillations in Salt Marsh Hydroperiod. Straight horizontal lines represent water levels at which a surface water connection between the tidal creek and the pond was established.

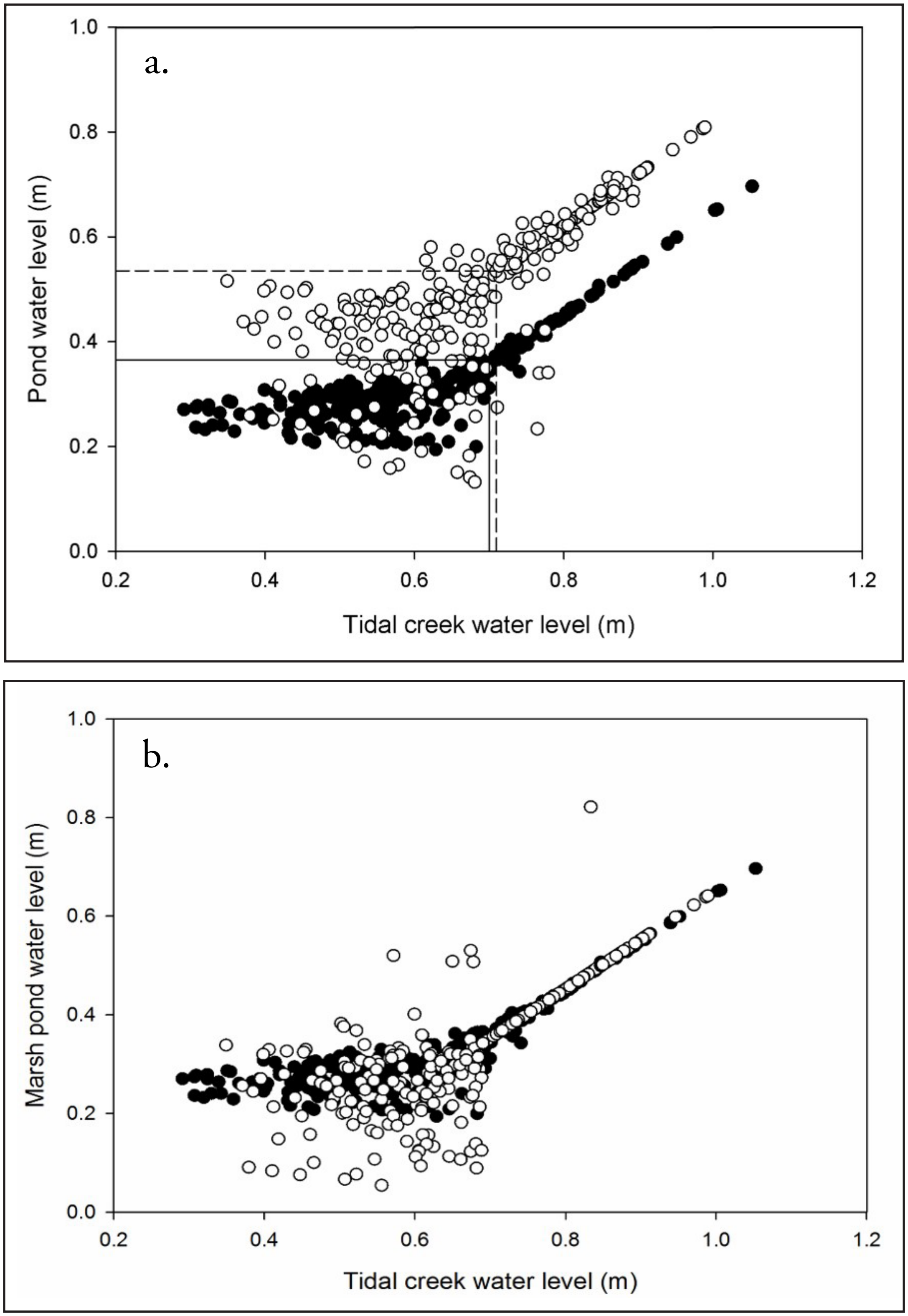

Figure 6. Observed and simulated temporal dynamics of mean daily water levels in the tidal creek and the marsh pond and the relationship between water levels in the creek and those in the pond. Solid lines and gray circles represent field data, and dotted lines and open circles represent simulated data. Straight horizontal and vertical lines represent water levels at which a surface water connection between the tidal creek and the pond was established. **6a** represents results without adjusting model elevations and **6b** represents model results after calibrating model elevations to match field values.

November 2003, 25 March 2004, and 7 April 2007 (Figure 5b) and did not simulate one event (26 October 2003) that occurred during the field study. There was also one connection event observed in the field (May 2004) that lasted for 15 days, whereas SLOSH simulated a connection event lasting 20 days (Figure 5b).

Discussion

Surface water level data from BR creek and the adjacent coastal pond indicate a clear point of connection/disconnection that allows us to better understand the timing of hydrologic connection events along a bay-tidal creek-marsh-pond continuum. These data also show that the seasonal pattern of fluctuations in bay water levels is associated with the frequency and duration of connection events across the ANWR marsh and ponds. Data from other creek-pond sites in the ANWR marsh show the same pattern, allowing for a larger-scale analysis (S. Davis unpublished data). It is important to note that the SLOSH was parameterized from a four-year field dataset when there were no large precipitation events that could impact marsh hydroperiod—this dataset provided a unique opportunity to explore marsh inundation being driven by a single factor (tides) without teasing apart other environmental interactions. In general, high creek water levels—and subsequent high frequency and duration of pond connection events—observed in the fall correspond with highest median bay water levels that typically occur in September and October of each year. The lowest creek water levels and frequency of pond connection occurred during the height of the winter (i.e., December through February) coinciding with long-term bay water level data.

Interestingly, whooping cranes historically begin arriving at the ANWR during mid-October after their nearly 2,500 mile fall migration from Wood Buffalo National Park in northeastern Alberta, Canada (Hunt and Slack 1989; Chavez-Ramirez 1996). Thus, they arrive during the period of highest connectivity between marsh ponds and the San Antonio Bay and feed heavily on the nekton resources (e.g., blue crabs) in these ponds. During these periods of high connectivity, there is a physical connection between marsh ponds and bay water, providing the potential for blue crab recruitment into marsh ponds from the bay and the continued availability of this key food resource for cranes. However, whooping cranes do not begin spring migration back to their Canadian breeding grounds until mid-April. Thus, the remainder of their stay at the ANWR coincides with the period of lower marsh-San Antonio Bay connectivity (December through February). The isolation of marsh ponds during lower water levels can lead to elevated evaporation, increased water column salinity, and lower blue crab abundance, as whooping cranes forage and remove crabs from marsh ponds. These factors, coupled with lower ambient winter temperatures, represents a critical period for the whooping cranes when thermal regulation and foraging are necessary for survival (Stehn 2003, 2004, 2005). Here, SLOSH can be used as a rapid assessment tool by coastal managers to determine the degree of hydrologic connectivity between bay water and marsh ponds, the potential shifts in connectivity patterns, and the subsequent availability of nekton food resources across the marsh landscape.

Summertime hydrology has been shown to have a clear impact on winter vegetation dynamics in the coastal marshes of the ANWR. Wozniak et al. (2012) found that mean summertime salinity in San Antonio Bay is directly linked to winter fruit production by the Carolina wolfberry (*Lycium carolinianum*), another key food resource for the whooping crane. SLOSH can be used here as an additional assessment tool to determine how summertime water levels and bay water column salinity work in concert to influence winter food resources. Specifically, SLOSH can determine if higher salinity summer water is hydrologically connected to coastal marsh ponds during periods of lower water levels; conversely, during high water level connection events, the salinity of the flooding water can be documented, as it is a critical indicator of the abundance of wolfberry fruit during the winter period (Wozniak et al. 2012).

Hydrological connectivity in salt marshes varies across both spatial and temporal scales and is controlled not only by tides but also by micro-elevational changes across the landscape. The degree of connectivity across the landscape is a significant driver for both the formation of the heterogeneous habitat types and for the distribution of energy, material, and nutrients throughout the marsh. Previous approaches to understanding landscape-level hydrologic connectivity patterns have required either long-term monitoring or spatially explicit modeling (Poulter and Halpin 2008). The former is expensive and time-consuming, while the latter has been limited by coarse-scale digital elevation models (DEM) on which to base flow dynamics (Park et al. 1989; Moorhead and Brinson 1995; Nicholls 2004). However, the increasing availability of high resolution DEMs and an increased focus on marsh response to climate change and sea level rise only improves our ability to model inundation in both riparian and coastal ecosystems (Alizad et al. 2016; Bales et al. 2007; Byrd et al. 2016; Poulter and Halpin 2008). Our study shows the potential for coupling the two approaches in a rapid assessment tool. We used a relatively short-term field data set to parameterize and evaluate a simulation model (SLOSH) that used high-resolution lidar data to determine connectivity patterns within the coastal wetlands of the ANWR.

Many hydrological processes are scale-dependent (Holmes et al. 2000; Kenward et al. 2000; Omer et al. 2003; Kienzle 2004). The spatial resolution of the lidar used by SLOSH allowed us to capture the fine-scale (i.e., micro-elevational) topographic features that can affect overland flow in the salt marsh of the ANWR. Lidar data increase the spatial resolution of elevation data by orders of magnitude compared to previously available DEMs for the ANWR (e.g., previous DEMs available mapped elevations in 30 m x 30 m cells, compared to the 1.4 m x 1.4 m [4.59 ft x 4.59 ft] cells of lidar images used here). Further, both field observations and results from SLOSH indicated that micro-topography and tidal fluctuation are driving factors for hydrological connectivity patterns at the ANWR. SLOSH captured the temporal dynamics of water fluctuations of both the tidal creek and inland marsh pond; however, the water level in the pond (i.e., pond depth) differed between the simulated and observed ponds by approximately 17 cm (6.69 in; Figure 6a). This lack of fit between simulated and observed water levels could have resulted from three sources: (1) the laser used to collect the lidar data not penetrating the water column during the initial survey; (2) an error in estimating the elevation of certain cells; or (3) the relative elevations obtained in the field not being standardized to the NAVD88 geodetic datum. Likely the error resulted from a combination of the three sources. The model can be calibrated by adjusting in-model elevation to correct for these errors (Figure 6b). It is important to note that the simulated hydrological connection point only differed by 1 cm (0.39 in) from the connection point observed in the field. From an ecological point of view, this is an acceptable range of error because we were not attempting to simulate hydrodynamics at a predictive scale but rather were attempting to capture the patterns in connectivity that could be used to infer ecological response. SLOSH is intended to be used as a rapid assessment tool to inform natural resource decision making and made several simplifying assumptions. However, SLOSH was able to capture the pattern of hydrologic connection events, providing useful insight into how hydrologic connectivity can regulate the transfer of energy, nutrients, and biota between the bay, tidal creeks, and inland marsh ponds.

Temporally, SLOSH captured all but one of the connection events between the tidal creek and the inland marsh pond; however, SLOSH generated three connection events that did not occur during the field studies. Each of the four disparate events resulted from the error associated with the regression predictions. During periods of disconnection, water loss in SLOSH was greater than observed in the field. Increased water loss in the model may have been attributed to the Hargreaves ET equation in SLOSH, which considered both temperature (observed at the ANWR) and solar radiation data (Hargreaves et al. 1985). We chose the Hargreaves equation because it was the most parsimonious of the ET equations we considered. There are several other empirical estimations of ET, including the Thornthwaite equation (Thornthwaite 1948), among others (refer to Mitsch and Gosselink 2007 for other references), and future versions of SLOSH could explore those estimations as well. Further, SLOSH only estimated water levels via regional bay water levels and losses via ET. This initial version of SLOSH was not parameterized to account for any other processes, such as direct precipitation, infiltration, or wind and/or barge effects that can affect inland marsh water levels.

We recognize that there are numerous factors affecting connectivity patterns and that overland flow is a complex phenomenon. Our goal, however, was to develop the most parsimonious model possible that captured the dynamic patterns of hydrological connectivity across a salt marsh at a relatively fine spatial scale (in this case 1.96 m^2 [21.10 ft^2]). SLOSH captured these general trends in marsh dynamics. Future research should include using SLOSH to determine at what spatial scale connectivity patterns are no longer captured and validate that with a more detailed field study as well as hindcasting marsh-pond connection events based on archived bay water level data going back to 1996. This will provide us with a better understanding of the frequency and duration of connection events that could potentially affect the abundance and distribution of food supplies and nutrients across the inland marsh landscape, which is not only important for marsh natural resource and whooping crane population management but will also allow us to have a foundation for understanding inland marsh functionality.

SUMMARY

The results from this study indicated that SLOSH has considerable potential for rapidly assessing inland marsh connectivity in salt marsh ecosystems. SLOSH is a dynamic simulation tool capable of generating connectivity patterns observed in the field with relatively little associated error, is a relatively low-cost method for capturing hydrological connectivity in inland marshes, and provides the foundation for more detailed assessments of how hydrologic connectivity events regulate the availability of critical food resources for migratory wading birds, including the endangered whooping crane. Lidar is readily available through coastal mapping programs of multiple federal and state agencies. SLOSH was parameterized from a time series of water level data that was collected when marsh inundation was being driven by tidal dynamics. As such, it provides a foundational level approach for understanding inundation during drought conditions. The SLOSH clearly captures the fine-scale hydrologic dynamics of the study site at the ANWR, which, in turn, created a spatially heterogeneous pulse-dependent landscape. Further, by modeling the pulsing structure of salt marsh hydrology, we have the underlying foundation on which to begin to understand how additional drivers (precipitation, wind, etc.) can impact the distribution and abundance of nutrients, organisms, and other natural resources across coastal marsh landscapes.

ACKNOWLEDGMENTS

We would like to thank the Guadalupe-Blanco River Authority, San Antonio River Authority, San Antonio Water System, Texas Water Development Board, U.S. Fish and Wildlife Service (particularly the staff at the ANWR) for providing financial and logistic support for the field studies and preliminary modeling efforts. The Environmental Laboratory of the U.S. Army Engineer Research and Development Center provided funding to Todd M. Swannack to complete this work. Three anonymous reviewers provided comments that truly strengthened the manuscript. C. Klimas and D. Shafer provided two excellent reviews. We also would like to thank R. Butzler, T. Hart, M. Driffill, and C. Miller for collecting the field data, A. Snelgrove for her technical assistance with GIS applications, M. Huston for productive discussion, and C. Morgan for providing helpful comments regarding modeling the soil-water interface along the Gulf Coast.

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