Simulated Holocene, Recent and Future Accretion in Channel Marsh Islands and Impounded Marshes for Subsidence Mitigation, Sacramento-San Joaquin Delta, California, USA

Steven J. Deverel[1], Judith Z. Drexler[2], Timothy Ingrum[1] and Christina Hart[1]

[1] HydroFocus, Inc., Davis, CA,
[2] US Geological Survey California Water Science Center, Sacramento, CA

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INTRODUCTION

Prior to 1850, the Sacramento-San Joaquin Delta was a freshwater tidal wetland which formed during the last 7,000 years as the result of rising sea level. This created a situation in which anaerobic conditions retarded decomposition relative to organic production and accumulation of inorganic material resulting in 1,400 km^2 tidal freshwater marsh and over 5 million cubic meters of organic deposits or peat in the Delta (Atwater et al. 1977, Shlemon and Begg 1975; Drexler et al., 2009a). Using radiocarbon dating, Drexler et al., 2009a,b estimated that the peat deposits of the Delta formed approximately 6,700 calibrated years before present (the range of possible dates is 6,030 to 6,790 years before present where present" is defined as 1950.

Peat accretes when organic matter accumulates at a faster rate that it decomposes (Boelter and Verry 1977, Mitsch and Gosselink 2000). In tidal wetlands, peat generally progressively accretes concomitantly with sea level rise but not always on a one to one basis during any specific time interval (Jelgersma et al. 1993, Mitsch and Gosselink, 2000). During the last 7,000-10,500 sea level rose in the San Francisco Estuary and Sacramento-San Joaquin Delta at a rate of about 1.7 mm/year. The primary factors controlling long-term peat accumulation are climate, plant community dynamics, tectonics, and hydrological processes (Siegel 1983, Jelgersma et al. 1993, Mitsch and Gosselink 2000).

In the Delta these factors were overshadowed by anthropogenic impacts during the transition from "pre-settlement" (~10,500 years BP to ~300 BP) to "post-settlement" (~300 years BP to present), during which there was a great increase in population and corresponding environmental disturbance. The greatest impacts to Delta ecosystems began in the late 1800s when most of the Delta was levied, drained, and brought under cultivation (Matthew et al., 1931; Thompson, 1957). Such disturbance in the Delta resulted in subsidence or the lowering of the elevation of peat relative to sea level. Although causes of subsidence include mechanical compaction, wind erosion, groundwater pumping, anaerobic decomposition, and dissolution of carbon, in the Delta the chief cause of subsidence is microbial oxidation of the organic, peat soils (Weir 1950, Prokopovitch 1985, Deverel and Rojstaczer 1996). Shallow subsidence due to microbial soil oxidation, wind erosion, burning, and consolidation has decreased over time due to changing land management practices and decreasing soil organic-matter content. Deverel and Leighton (2008) reported present-day rates ranging from less than 1 to 3 cm/year. During the first half the 20th century, Weir (1950) measured subsidence rates greater than 7 cm/year.

Drexler et al. (2009b), Atwater (1980), Atwater et al. (1979), Shlemon and Begg (1975) documented some of the factors affecting accretion and estimated rates of peat accumulation in the Sacramento-San Joaquin Delta. Atwater (1980) and Atwater et al. (1979) mapped the extent of Delta peat deposits and thickness. They also described the Holocene history of the Delta and the ecology and statigraphy of channel marsh islands. Shlemon and Begg (1975) used ^{14}C dating from various locations throughout the Delta to estimate peat accumulation rates, sea level rise and developed a model for peat formation. However, due the sparseness of their data, Shlemon and Begg (1975) lacked definition and specificity for estimating the spatial and temporal viability in accretion rates. Moreover, their data provides little insight about the spatially variable processes affecting marsh accretion.

More recently, Goman and Wells (2000) determined vertical accretion rates for two peat cores collected at Browns Island, one of the sites chosen for this study. They used linear models and found high variability in accretion with depth (0.05 - 0.41 cm yr-1). Using extensive ^{14}C, physical and chemical data for cores distributed throughout the Delta, Drexler et al. (2009b) provided essential insight into spatially variably accretion processes in the Holocene Delta. Specifically, Drexler et al. (2009b), identified fundamental differences in processes resulting in accretion rates on islands subject to greater fluvial deposition where sediment input was more dominant (e.g. Browns Island) and those where organic accretion predominated under more quiescent hydrogeomorphic conditions (e.g. Franks Wetland).

The State of California is interested in promoting impounded marshes for reversing the effects of subsidence on subsided Delta islands. In the 1990's, HydroFocus, Inc. and US Geological Survey personnel demonstrated that managed, impounded marshes, which promote production of emergent wetland vegetation, can result in a net carbon gain (Deverel el al, 1998; Miller et al, 2000). In 1997, the Department of Water Resources, Reclamation District 1601, the US Geological Survey California Water Science Center (USGSCSWC) and HydroFocus, Inc. created a 15-acre impounded marsh on Twitchell Island (see Miller et al, 2008) to evaluate the long-term potential for peat accretion. The marsh consists of two approximately equal-sized ponds with different water management practices. The west pond water depth is maintained at approximately 25 cm whereas the east pond water depth is maintained at about 55 cm. From 1997 to 2008, wetland-surface elevations in the Twitchell Island impounded marsh increased by an average of about 3 cm/yr but the rates at different sites in the marsh ranged from -0.5 to +9.2 cm/yr (Miller et al., 2008). Accretion varied spatially and was dependent on water depth, plant community composition, marsh maturity, and water residence time. Miller et al. (2008) reported that the greatest rates occurred in areas of the deeper wetland with dense, mature stands of emergent vegetation (*Schoenoplectus and Typha species*).

Vertical accretion rates of admixtures of inorganic and organic material which from peat determine the elevation of a marsh relative to the tidal frame (e.g., Redfield 1972, Stevenson et al. 1986). Little is currently known about the temporally variable rates of peat accretion in the Delta. Better understanding of peat accumulation rates and processes affecting accumulation will aid in the development of impounded marshes for mitigating subsidence on Delta islands and provide time estimates for future accretion. Knowledge of vertical accretion rates are also of key importance to managers tasked with choosing the best sites for restoration of tidal marshes to improve habitat for sensitive species and the future survival of existing tidal marshes. Unless tidal marshes can maintain a certain elevation in the tidal frame through adequate vertical accretion, they will ultimately be “drowned” due to future, increased rates of sea-level rise.

For this paper, our primary purpose was to improve the understanding of accretion rates and processes affecting rates on channel marsh islands and in impounded marshes and to predict future accretion in managed impounded marshes for subsidence reversal and possible future elevation changes in tidal marsh islands. Because of the short time series of data and limited understanding of long-term accretion in impounded marshes, we initially hypothesized and later observed that a synthesis of data for both long-term accretion during the last 5,000 years in Delta channel marsh islands and during the last decade in the impounded marsh on Twitchell Island would provide important insights into probable future accretion in impounded marshes on subsided Delta islands. We herein describe the results of computer modeling which we have used as a synthesis and predictive tool for peat accretion processes in the Delta. Specifically, we used a modified cohort accounting model developed by Callaway et al. (1996) to simulate accretion during the last 4,650 years and t on two Delta channel marsh islands; Browns Island, and Franks Wetland (Figure 1). We have also used the model to simulate accretion rates in the Twitchell Island impounded marsh. Lastly, we report the results of future simulations to estimate the potential for long-term accretion in impounded marshes on subsided islands and tidal marshes in the Delta.

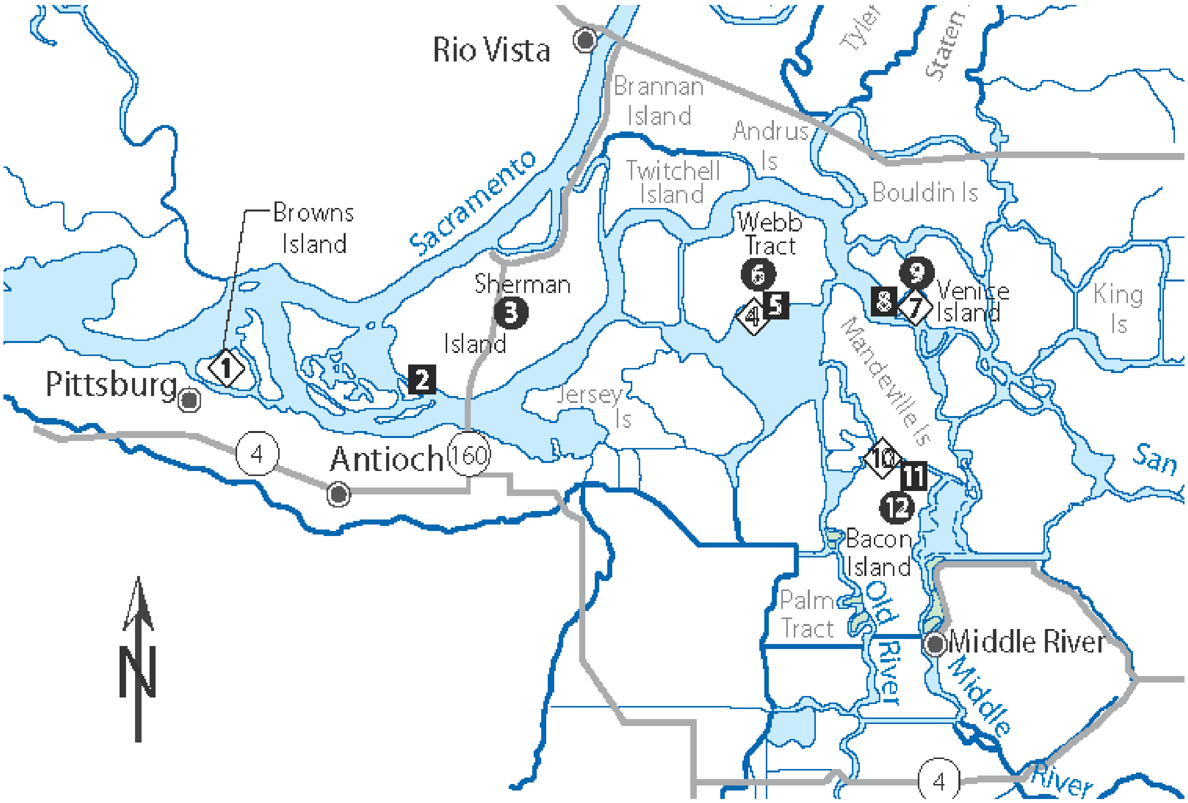

Figure 1. Location of Browns Island, Franks Wetland and Twitchell Island.

Wetland Accretion Modeling

Several researchers have used models to simulate accretion processes in wetlands. French (1993) and Allen (1990) developed algorithms to simulate sediment deposition in salt marshes without fully considering processes affecting organic matter deposition. Similarly, Krone (1985) created a model for marsh development in the San Francisco Bay that focused primarily on inorganic sediment related processes and did not fully consider organic matter deposition. Cohort accounting is a common approach to wetland accretion modeling which uses input values for surface wetland inputs (surface cohorts) and processes and accounts for changes as the cohorts become buried in the marsh. Morris and Bowden (1986) and Chimura et al. (1992) were the first to develop a sediment cohort model designed specifically to simulate accretion under different sea level rise scenarios but was limited by its inability to distinguish between mineral and organic inputs. Frolking et al. (2001) simulated peat accretion using the peat decomposition model which did not fully consider sediment deposition.

Calloway et al. (1996) used the cohort accounting approach to simulate about 300 years of accretion in tidal marshes in the southeastern United States and England. Rybczyk et al. (1998) extended the Calloway et al. (1996) model to simulate elevation changes as affected by seal level rise in a forested wetland in the southeastern United States. Rybczyk and Cahoon (2002) and Day et al. (1999) used a similar approach to simulate effects of sea level rise on wetland accretion in Louisiana and the Venice Lagoon, respectively. Because of its unique and demonstrated ability to simulate the key processes affecting marsh accretion, for this study, we have used the Calloway et al. (1996) cohort accounting model to simulate accretion of wetland sediments.

The Callaway et al. (1996) model requires inputs for surface organic matter and mineral deposition, subsurface organic matter decomposition, below ground organic matter production, consolidation, initial and final porosities, sea level rise, tidal range, organic and mineral particle densities. We used different approaches for simulating accretion for channel marsh islands (Browns Island and Franks Wetland) and the Twitchell Island impounded marsh. For the channel marsh islands, key unknown variables were organic matter and mineral deposition and organic-matter decomposition rates. We estimated mineral deposition using geochemical data for cores collected during the study. For organic matter deposition and decomposition rates, we conducted an extensive literature search and used values from the literature (see summary below) to initially estimate and place bounds of the model input values for these variables during the calibration process. Data for porosity, bulk density and organic-matter content described in Drexler et al. (2009a, b) were used to estimate and calibrate variables affecting consolidation.

For the Twitchell Island impounded marsh simulations, more data were available for estimating model inputs such as measured inorganic and organic inputs and decomposition rates. Additionally, data for bulk density were used to develop and adjust input variables for consolidation. Measured organic matter content and elevation changes were also used to calibrate and validate the model.

Surface Organic Matter and Sediment Deposition

We attempted to gather information relevant to conditions in the Sacramento-San Joaquin Delta. Table 1 summarizes the result of our literature search from which we selected articles presenting data for surface organic inputs from the Delta and other areas. The US Geological Survey provided organic deposition rates for the Twitchell Island impounded marsh (Miller and Fujii, 2008). Average organic matter deposition in the in a *Typha* dominated impounded marsh ranged from 0.05 to 0.6 g/cm^2-year from 1998 to 2006. The lowest rates were associated with deeper and open water.

Reed (2002) evaluated organic and recent sediment accumulation rates in natural and restored marshes in the western, northern and central Delta. She reported organic matter deposition rates ranging from 0.65 to 2.83 g/cm^2-year. Inorganic matter deposition rates ranged from 1.8 to 22.6 g/cm^2-year. The highest rates of inorganic matter accumulation were at sites closest to the San Joaquin River and lowest rates were in the interior marshes. She observed that vegetation growth was fairly consistent among the study areas, with only a minor variation in species which were primarily *Schoenoplectus (*formally called *Scirpus), Typha,* and *Phragmites* species.

Most other values reported in the literature for natural wetlands were substantially lower than those reported by Reed (2002) and the US Geological Survey. For example, Bakkar et al. (1997) conducted a survey of organic accumulation rates in fens and bogs from various study areas and identified lower organic accumulation with increasing latitude. Their reported accumulation rates ranged from 0.004 g carbon/cm^2-year (in a boreal bog in Russia) to 0.045 g carbon/cm^2-year (in a subtropical fen in Florida and a tropical bog in Kalimantan (Borneo). For data for tidal marshes described in Table 1, the average organic matter accumulation rate was 0.22 g organic matter/m^2-year. Excluding the Reed (2002) data which are outliers for the literature and relative to the Twitchell impounded marsh data (Miller and Fujii, 2008) resulted in average value of 0.05 g organic matter/cm^2-year.

Table 1. Summary of surface organic accumulation rates.

Source	**Species/ habitat**	**Organic matter accumulation rate (g/cm2-year)**
Day et al, 2004.	Mississippi Delta tidal freshwater swamplands converted to receive treated wastewater.	0.0276 prior to receiving wastewater, 0.074 after receiving wastewater
Delaune and Pezeshki, (2003), measured accumulation rates and carbon content of accumulating sediment.	*Spartina sp.* Mississippi Deltaic Plain coastal salt marsh	0.044 to 0.0812

Source	Species/ habitat	Organic matter accumulation rate (g/cm2-year)
Cahoon, 1994, measured accumulation rates and organic matter content of accumulating sediment.	Spartina and unnamed freshwater species, fresh to saline gradient, Louisiana, USA	0.013 ± 0.004
Craft and Richardson, 1993	*Cladium jamaicense* (sawgrass) in freshwater wetland of Florida Everglades, USA	0.281
Miller and Fujii (2008)	emergent shoots, emergent roots in impounded marsh on Twitchell Island in the Sacramento-San Joaquin Delta	between 1998 and 2006 average values ranged from 0.05 ± 0.013 to 0.60 ± 0.04
Neubauer et al. (2002); estimated from accretion rates and carbon content of accumulating sediment.	*Peltandra virginica* and *Pontederia cordata*, Virginia, USA, freshwater tidal marsh.	0.134 ± 0.07
Neubauer (2008)	Evaluated organic matter accumulation in freshwater tidal marshes in southeast, northeast and Gulf Coast, USA. Vegetation varied.	average values for each area include Northeast – 0.0324 Southeast – 0.0689 Gulf Coast – 0.0426
Nyman and Delaune (1999) compiled organic accumulation rates from previous studies for coastal marshes		0.028 – 0.174
Reed, D.J., 2002, measured accumulation rates and organic matter content of accumulating sediment.	*Schoenoplectus, Typha and Phragmites spp.* in the western Sacramento-San Joaquin Delta.	1.51 (ranged from 0.70 to 2.32)
Smith, et al., 1983	*Spartina alterniflora* (salt marsh), *Spartina patens* (brackish marsh), *Panicum hemitomon* (freshwater marsh) in Louisiana, USA	0.0296 (brackish), 0.0224 (freshwater)

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Besides the values provided by Reed (2002), we are unaware of published surface inorganic sediment inputs that are relevant for model inputs for Delta tidal marshes. For the Twitchell impounded marsh which received a constant supply of San Joaquin River water, Gamble et al. (2003) and data provided by the US Geological Survey (Jacob Fleck, USGSCWSC, Sacramento, CA, written communication, 2006) indicate spatially averaged sediment deposition rates of about 0.03 g/cm^2-year.

Organic Matter Decomposition

A key input for modeling wetland accretion is the rate of decomposition of surface and subsurface organic inputs and reported variables significantly influencing decomposition include flooding duration, sediment input and species. Other significant variables, including water flow, fragmentation by litter fauna, water salinity, and temperature, were reported but with less frequency. Litter decomposition rate of litter mass loss were inversely correlated with duration of flooding (e.g. Anderson and Smith, 2002; Atkinson and Cairns, 2001; Connor and Day, 1991; Battle and Golladay 2001). Sedimentation can inhibit the decomposition of wetland litter. For example, Vargo et al. (1998) reported faster decomposition for wetlands where sediment was not applied compared to wetlands with single and multiple sediment applications. Wang et al. (1994) observed that burial of litter inhibited decay initially. Hackney and de la Cruz (1980) found that decomposition rates varied with depth and material in deeper decomposition bags decomposed more slowly than shallow bags.

Sediment can also bring nutrients into the wetland and increase decomposition rates (e.g. Hietz, 1992). Connor and Day (1991) noted that burial of organic matter and nutrients by stagnant wetlands inhibited decomposition. Some studies illustrate decomposition enhancement as the result of nutrient inputs (e.g. Lee and Bukavekas, 2002; Corstanje et al., 2006. However, Vargo et al. (1998) found that decay was not significantly different in treatments of phosphorus-enriched clay and un-enriched clay.

Organic decomposition is typically modeled as an exponential decay function (equation 1).

$$\text{Fraction of initial mass remaining} = \exp(-k_{decomp} \times \text{time}) \qquad (1)$$

The value of k_{decomp} is usually determined from measurements of remaining mass in decomposition bags that are harvested at varying times after initial placement. We surveyed the literature to determine a range of values for k_{decomp} in equation 1. We focused on determining k_{decomp} for similar conditions to the Sacramento-San Joaquin Delta tidal wetlands and for similar plant types reported form the Delta peat deposits (*Typha, Schoenoplectus and Phragmites* species.). In many cases, decomposition was expressed in values of k_{decomp} in the reviewed articles. In others, we determined k_{decomp} from data provided in the article.

There are variations in decomposition rates among species in similar environments. For example, Atkinson and Cairns (2001) reported decay constants of 0.37 yr-1 and 0.29 yr-1 for *Typha latifolia*, and 0.11 and 0.22 yr-1 for *Schoenoplectus cyperinus*. Davis and van der Valk (1978) observed less mass loss in *Typha glauca* than for *Schoenoplectus fluvialitis* in submerged litter bags, but similar mass loss for both species in standing litter. Reported decay constants ranged from 0.29 to 1.7 yr^{-1} for *Typha* species, and from 0.11 to 1.64 yr^{-1} for *Schoenoplectus* species. For the 20 studies reviewed for temperate and tropical-zone wetlands (see Table D1 in Appendix D), k_{decomp} values ranged from 0.05 to 5.4 yr^{-1}; the mean was 0.782 yr^{-1}. The inner quartile ranged from 0.245 to 0.785 yr^{-1}. For the studies conducted in climatically comparable areas (Lee and Bukaveckas, 2002; Anderson and Smith, 2002; Moran et al, 1989; Conner and Day, 1991; Lee, 1990; Corstanje et al, 2006; Murayama and Bakar, 1996; Chimner, and Ewel, 2005; Hackney and de la Cruz, 1980), the mean and median k_{decomp} values were equal to 1.0 yr^{-1} and values ranged from 0.075 to 27.38 yr^{-1}. The inner quartile ranged from 0.550 to 2.08 yr^{-1}.

Sea Level Rise

About 6,200 years ago, sea level rose to reach Browns Island at the western edge of the Delta (Goman and Wells, 2000; Shlemon and Begg, 1975). There are few estimates of rates of sea level rise during this last 6,000 years. In their study of cores collected in San Francisco Bay, Atwater et al. (1977) indicated a rate of sea level rise of about 1.7 mm/year from 6,000 years to the present. Using a compilation of radiocarbon dates from the Delta and other locations in central California, Rosenthal and Meyer (2004) indicated sea level rise ranging from 1.33 to 1.54 mm/year since 7,000 years before present. Gornitz et al. (1997) estimated relative rates of sea level rise during the 20th century on the west coast of the United States as ranging from 1.4 to 1.5 mm/year. For future simulations, we used estimates from Meehl, et al. (2007) which provided global sea level rise projections to the end of the 21st century.

Subsidence Due To Gas and Groundwater Withdrawal

Delta tidal marsh accretion has been affected by subsidence due to natural gas withdrawal in the Rio Vista Gas Field. We have surveyed the literature and available data to estimate probable subsidence rates. Rojstaczer et al. (1991) estimated the possible effect of gas and groundwater withdrawal in the Delta by dating of sediment cores at undisturbed sites on Delta channel marsh islands which have remained at sea level thus indicating that accretion offsets sea level rise and any subsidence. They estimated recent sedimentation rates by analyzing the vertical sediment core samples for ^{137}Cs (Delauney et al., 1978). Five of 12 cores collected in late 1989 provided useful data and indicated accretion rates of 0.48 to 0.67 cm/year. (The five cores were collected on channel marsh islands north of Twitchell Island, east of Bradford Island, south of Webb Tract and east of Bethel Island, Figure 1). Rojstaczer et al., 1991 subtracted a eustatic sea level rise of 0.13 cm/year and estimated regional subsidence rates of 0.35 to 0.54 cm/year due to gas and groundwater withdrawal from 1963 to 1989. However, available data indicate a small amount subsidence due to groundwater withdrawal which is primarily for sparse domestic use on Delta islands. Kerr and Leighton (1998) reported inelastic compaction rates of about 0.05 cm/year from 1987 to 1993. See Appendix A for more information about the Rio Vista Gas Field and our estimates of subsidence rates due to gas withdrawal.

METHODS

Development of Inputs for Accretion Model

We used a modified version of the Callaway et al. (1996) cohort-accounting model to simulate peat accretion since about 4,650 years before present and recent accretion of inorganic and organic matter on Delta channel marsh islands and the Twitchell Island impounded marsh (Miller et al, 2008). We used results described in Drexler et al, (2009a, b) for cores collected on Franks Wetland and Browns Island to compare to simulation results. Elevations for the core locations were determined by Drexler et al. (2009a). We also estimated future rates of accretion. In the model, mineral and organic matter accumulated at the surface and associated pore space are moved to older age classes as time progresses and they become buried in the marsh. After the cohort is moved, changes in the composition, mass and porosity due to organic matter decomposition, consolidation and below-ground production are calculated. The model tracks the depth of the cohort to determine elevation in the accumulating sediment. We used a combination of literature values; model calibration and site-specific inputs for simulate accretion. Table 3 and Figure 2 show and describe the model inputs and illustrate model processes. We used an annual time step for all simulations.

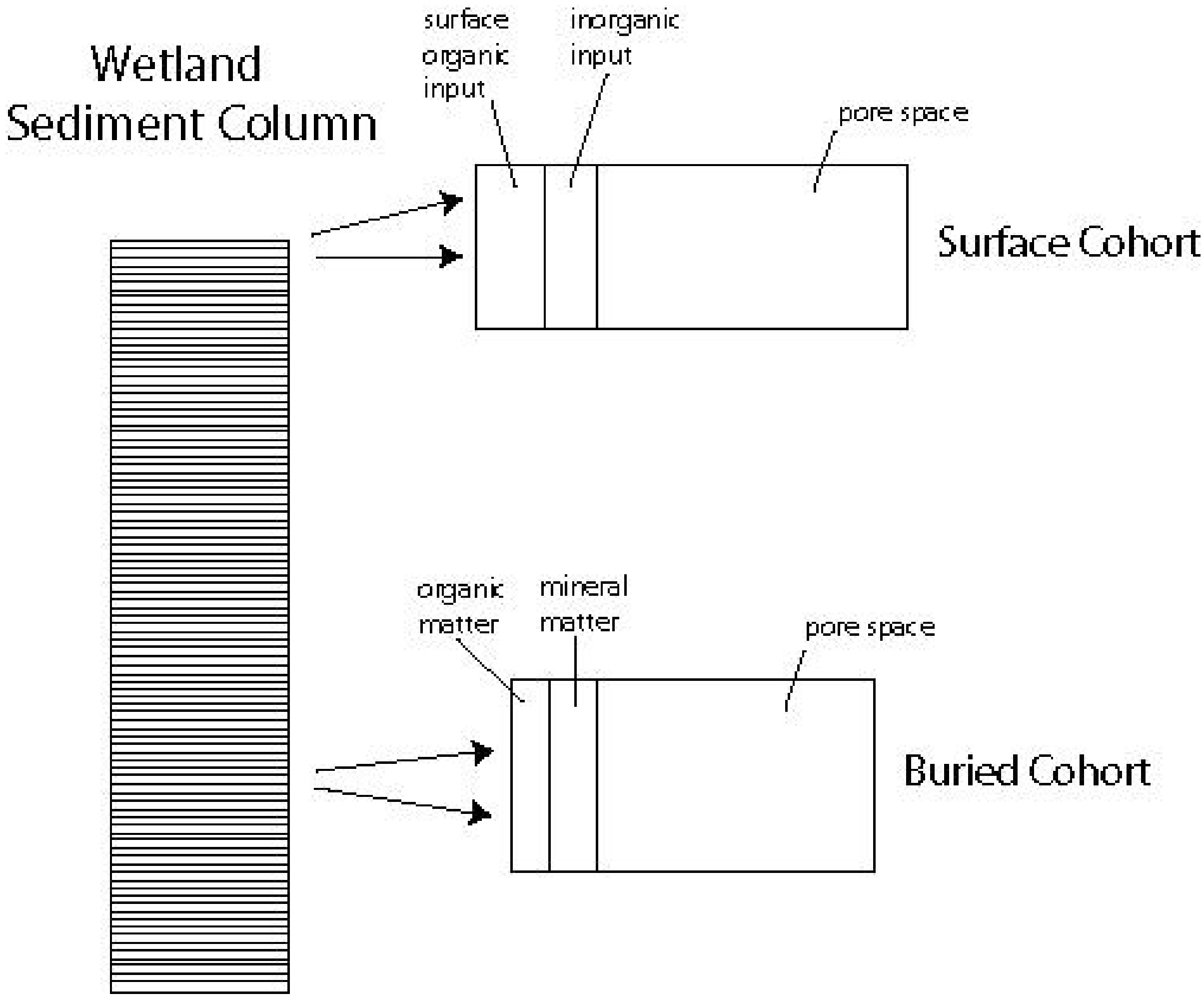

Figure 2. Diagram of the cohort-accounting process for simulation of wetland accretion (modified from Callaway et al, 1996).

Table 2. Model input parameters, variable names and data sources.

Parameter	Variable name	Data Source	Development of Input for model
Surface mineral matter deposition (g/ cm^2)	minin	Titanium concentrations in cores.	Available core age estimates and titanium concentrations (see Alpers et al., 2009) to estimate inorganic inputs. (see Appendix B).
Percent refractory organic matter	refrac	Literature and data for Twitchell Island impounded marsh.	We used a value of 0.20 for all simulations.
Surface organic matter deposition (g/ cm^2)	orgin	Calibrated for Browns Island and Franks Wetland	We initially used the 0.05 g/ cm^2 derived from the literature review and adjusted to match measured core values for organic matter content reported in Drexler et al. (2009b).
Below ground organic matter production (g/ cm^2)	undpro	Literature and data for Twitchell Island impounded marsh.	For the channel island simulations, we assumed undpro equaled orgin. For Twitchell, we varied undpro over time from 50 % or equal to orgin as the marsh matured based in data provide by the US Geological Survey.
Decomposition rate constants for year 1, 2, 3 and later, yr^{-1}	$K_{decomp,1,2,3}$	Literature and data for Twitchell Island impounded marsh.	For channel marsh islands, we specified the value of 1.0 based on the literature review. For Twitchell, we used spatially and temporally variable values determined from decomposition bag

			experiments reported by Miller et al. (2008) For the long-term Holocene modeling, decomposition declined to close to zero within 100 years after introduction to the marsh.
Initial pore space (fraction)	h2oin	Core data from Browns Island and Franks Wetland and Twitchell impounded marsh.	For channel islands, we used the largest reasonable porosity values. For Twitchell we estimated values from bulk density data and literature values for organic and mineral particle density.
Final pore space (fraction)	porelim	Core data from Browns Island and Franks Wetland and Twitchell Island wetland.	For all simulations, we varied porelim with time to accurately simulate measured bulk density. Input values were constrained by measured porosity values for Browns Island and Franks Wetland.
Consolidation constant (unit less)	K_{cons}	Calibrated value	We initially used values of 2 through 10 from experiments described in Appendix C. A final value of 10 was used for all simulations based on model calibration.
Sea level rise (cm/year)	slr	Literature	Specified as 0.17

			cm/year for all simulations except Twitchell.
Subsidence (cm/year)	subsid	Calculated from ^{137}Cs and ^{210}Pb data and information about gas production and pressures	See appendix A for explanation of development of time-variable subsidence inputs.
Organic particle density (g/ cm^2)	orgden	Set to 1.14 based on DeLaune et al.(1983)	
Mineral particle density (g/ cm^2)	Minden	Set to 2.61 based on DeLaune et al.(1983)	

For simulation of channel island accretion during the last 4,650 years to within the last several hundred years, we modified the model to allow varying annual inputs for mineral and organic inputs. For simulation of recent accretion (within the last 150 to 425 years), we modified the model to accept time varying inputs for first year decomposition rates, organic and mineral inputs, initial and final porosity and subsidence rates. Based on core ages determined from ^{14}C and ^{137}Cs, significant bulk density changes were apparent in the core for Browns Island within the last 150 years. For Franks Wetland, ^{210}Pb and ^{14}C ages indicated significant changes within the last 425 years.

Consolidation in the model is determined by the density of the material above a given cohort such that the annual decrease in cohort volume is equal to

$$1 - (c/k_{cons} + c) \qquad (2)$$

Where c is the density of the material above the cohort and k_{cons} (unit less) controls the rate of decrease in volume. For organic dominated systems, its value is greater than 1. Callaway et al. (1996) used values of 170 and 250 for his simulations of Siffkey and Biloxi wetlands in England and Louisiana. We obtained a calibrated value of k_{cons} for our modeling effort as follows. First, we used bulk density data collected before and after a sediment application in a wetland mesocosm on Twitchell Island described in HydroFocus, Inc. (2007) and Appendix C. Through trial and error using the modified Calloway et al. (1996) accretion model to simulate bulk density changes in recently deposited sediments in the mesocosms we determined that values of k_{cons} ranged from 2 to 10. We used these values as initial inputs to the simulations for the simulations for Browns and Franks. Through trial and error, we determined that a value of 10 was the best fit for these simulations. We also used a value of 10 for the Twitchell simulation. Accretion is highly sensitive to small changes in k_{cons}, porelim and h2oin (Calloway et al., 1996). Therefore, during future estimates of future accretion we varied these values to estimate uncertainty.

To provide an independent estimate of model inorganic input, we used titanium data for Browns Island and Franks Wetland. Titanium is not accumulated in plant tissue (Kabata-Pendias and Pendias, 1992) and can be used as a surrogate for mineral sediment in the core to provide an estimate for model inputs. We obtained titanium data from Alpers et al. (2009). Our calculations are described in detail in Appendix B.

For future accretion estimates for the entire Delta we used initial elevation data collected by the California Department of Water Resources using LIDAR (Light Detection and Ranging) in January and February 2007. LIDAR uses an aircraft-mounted instrument that measures surface elevations by emitting photons toward the ground and timing their return after they reflect. Since photons that are gone longer have traveled a farther distance, the instrument can construct high-resolution elevation data as it flies over and scans the ground. To create maps of time for accretion to current sea level, we downloaded and mapped these elevation data for the relevant areas of the Delta. Each pixel of the data represents a 10x10-m ground surface area with some associated elevation value. We used future accretion estimates to map areas of the ranges of years to reach sea level.

RESULTS

Using the available data for the Browns Island and Franks Wetland cores described in Drexler et al. (2009b), the Twitchell Island impounded marsh and the literature; we constructed historic and future accretion simulations. For the Browns and Franks Wetland cores, we utilized porosity and bulk density data to estimate values for initial and final porosities (h2oin and porelim, see Table 3). Subsidence was estimated from ^{137}Cs and ^{210}Pb data and information about changing pressures in the Rio Vista gas field (Appendix A). In conjunction with core age estimates, core titanium concentrations were used to estimate wetland sediment inputs (minin) (see Appendix B for more details). Additional model inputs such as organic matter input (orgin) and compaction constants were calibrated using a range of values consistent with the literature and data for Twitchell Island mesocosms (HydroFocus, Inc., 2007, Appendix C). More input data were available for simulation of the 12 years since California Department of Water Resources, US Geological Survey, Reclamation District 1601 and HydroFocus personnel flooded the Twitchell Island impounded marsh on what was previously agricultural land. These data included mineral and organic inputs as well as core data for bulk density and organic matter content and elevation changes measured with a sedimentation erosion table (SET) (Boumans and Day, 1993).

Simulation of Accretion on Channel Marsh Islands

Franks Wetland

We conducted two model runs to simulate the accretion record starting at 4,650 years before present, which represents a depth interval of 600 cm (Figures 3-6). Figures 3 through 6 show reasonable agreement with measured values for elevation, bulk density and organic matter content. During the recent-time simulation, we attempted to simulate the increased mineral input and associated bulk density in the top 100 cm (Figures 5 and 6). This increased sediment input appears to have resulted primarily from the increased sediment load in Delta channels that occurred during the late 1800's and early 1900's as the result of hydraulic mining in California (Gilbert, 1917)

For the simulation during the last 4,650 years, we used time-constant inputs shown in Table 3. We used an initial porosity value of 96 % based on core data. The final porosity was also estimated from core data. Consistent with the literature for tidal wetlands described above, the organic matter input was constant at 0.02 g/cm^2-year. Sediment input (minin) of 0.004 g/cm^2-year was based on the titanium data. Specifically, the average sediment input calculated from the titanium data (see Appendix B) was 0.004 g/cm^2-year for 15 core samples with age dates from 563 to 3,524 years before present. Values ranged from 0.001 to 0.007 g/cm^2-year. The average rate of accretion during this period was 0.12 cm/year.

Consistent with relatively quiescent accretion during the last 4,650 years, bulk density and organic matter content were relatively constant with depth from about -100 to -600 cm. Bulk density varied from 0.037 to 0.25 g/cm^3. However, larger values measured near the core bottom were probably the result of influence of underlying mineral sediments. Within 500 cm, values ranged from 0.04 to 0.10 g/cm^2. The mean simulated value was 0.08 g/cm^2. For the same depth interval, the organic matter fraction varied from 0.62 to 0.93. The mean simulated value was 0.83.

Figure 4 shows the simulation results for the upper 100 cm during (425 years) a substantially different hydrologic regime when sediment input and bulk density increased which increased the average accretion rate to 0.23 to 0.37 cm/year. Also, subsidence due to gas withdrawal began within the last 80 years which we simulated as ranging from 0.05 to 0.45 cm/year based on core ^{210}Pb data and gas production information described in Appendix A.

We estimated the sediment input from core titanium data. Specifically, the average sediment input calculated from the titanium data (see Appendix B) was 0.34 g/cm^2-year for 4 core samples with age dates from 22 to 108 years before present. The average model input for this time period was 0.22 g/cm^2-year. For the entire simulation, yearly input values varied to match bulk density data from 0.004 to 1 g/cm^2-year. Model sediment input increased starting in the 1870's and peaked in the 1930's. Sea level rise was equal to the 4,650-year simulation rate of 0.17 cm/year.

Organic inputs varied as described in Table 3. Consistent with increased sediment input and increased hydrologic change, sediment bulk density increased and the fraction organic matter decreased within the upper 100 cm relative to the accretion model results for the 4.650-year simulation.

Table 3. Key model inputs for different wetlands over time

Key Model Inputs	**Franks Wetland (4,650 years)**	**Franks Wetland (recent time)**	**Browns Island (3,330 years)**	**Browns Island (recent time)**	**Twitchell Island west pond (25-cm water depth)**	**Twitchell Island east pond (55-cm water depth)**
Initial porosity (h2oin) in percent.	96	95	93	91	88	94
Final porosity (porelim) in percent	93	Average = 89, ranged from 87 to 90	82	81	81	91
Organic matter input (orgin) in g/cm^2-year	0.025	Average = 0.14, ranged from 0.01	0.06	Average = 0.17, ranged from	Average = 0.47, ranged from 0.22	Average = 0.22, ranged from 0.17

		to 0.6			in early years to 0.63 in later years.	to 0.30
Mineral input (minin) in g/cm^2-year	0.004	Average for entire simulation = 0.22, (ranged from 0.004 to 1)	Average for entire simulation = 0.07 (ranged from 0.0125 to 0.075)	Average = 0.044, ranged from 0.01 to 0.1	Average = 0.17, ranged from 0.02 in recent years to 0.6.during initial years.	Average = 0.024, ranged from 0.007 in recent years to 0.08.during initial years.
First year decomposition constant (k_{decomp}) in year^{-1}	1.00	1.00	1.3	1.3	0.41	1.4
Sea level rise (slr) in cm/year	0.17	0.17	0.17	0.17	0.0	0.0
Subsidence during the past 80 years in cm/year	0	Average = 0.28	0	Average = 0.11	0	0
Average accretion rate for peat and recently accreted inorganic and organic matter in cm/year	0.12	0.23 for last 425 years, 0.37 during last 150 years	0.11	0.3 during the last 150 years.	2.5 from 1997 to 2008.	1.7 before 2003, 7.4 after 2003.

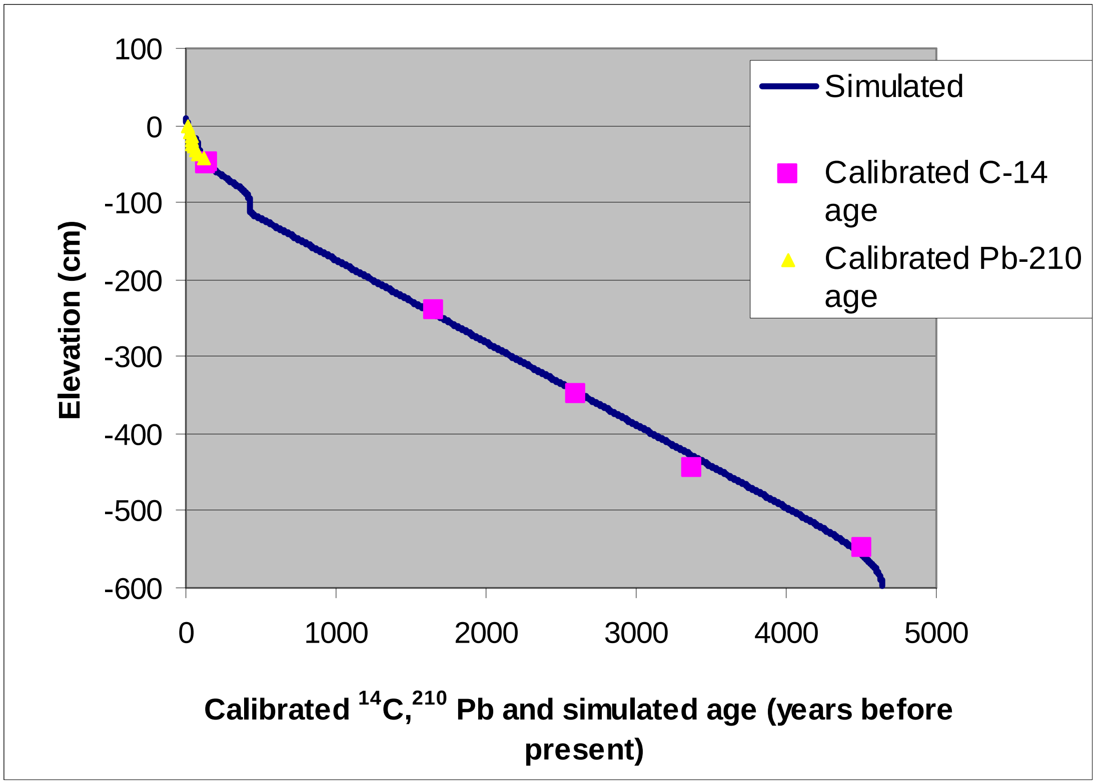

Figure 3. Simulated and measured accretion for Franks Wetland. Elevation is relative to mean sea level.

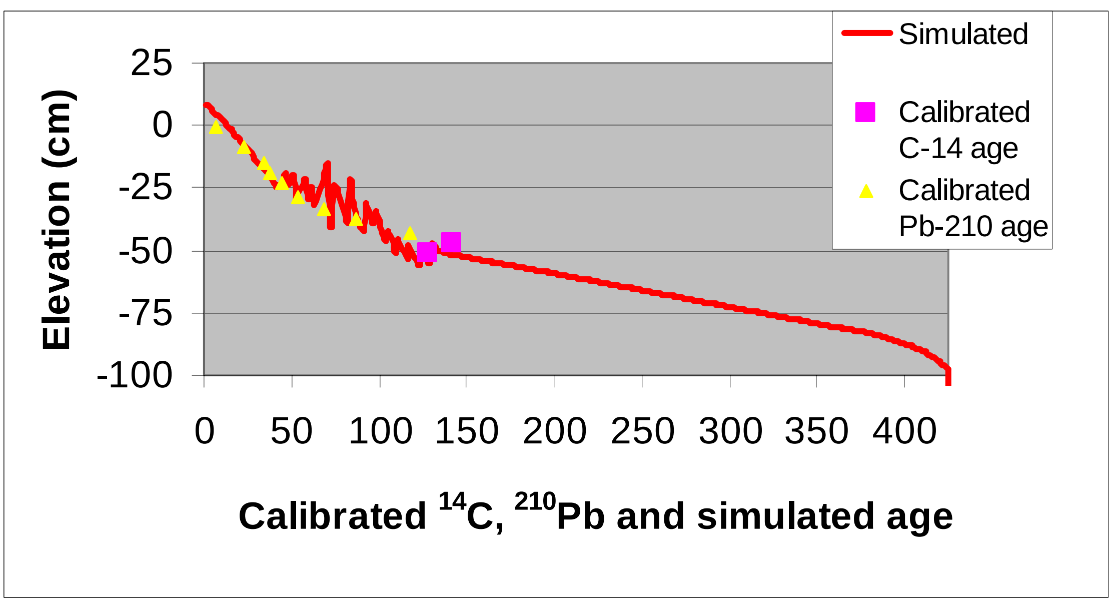

Figure 4. Simulated and measured accretion for Franks Wetland during the last 425 years. Elevation is relative to mean sea level.

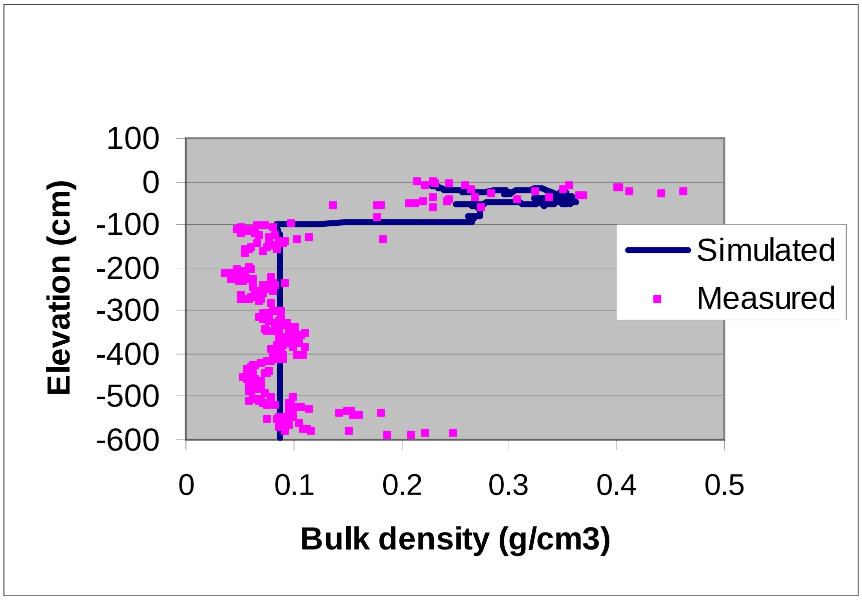

Figure 5. Measured and simulated bulk density for Franks Wetland. Elevation is relative to mean sea level.

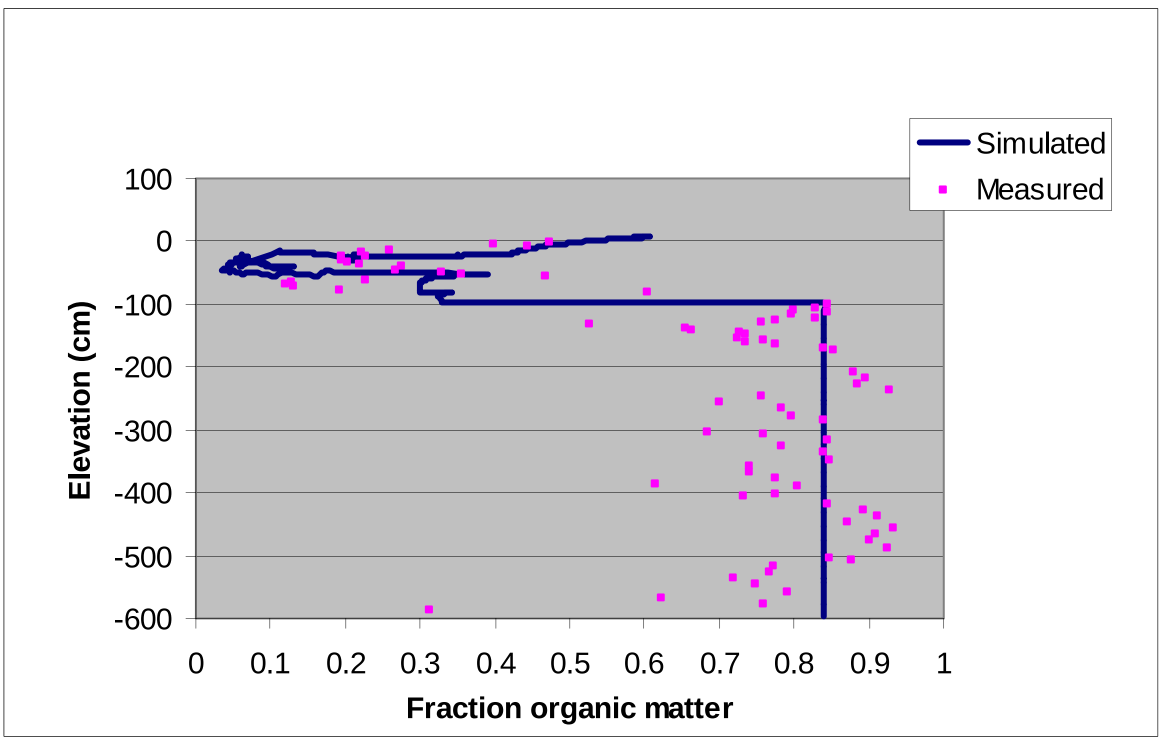

Figure 6. Simulated and measured organic matter content for Franks Wetland. Elevation is relative to mean sea level.

Browns Island

In contrast to Franks Wetland, accretion on Browns Island was characterized by periodic influxes of high sediment inputs from about 3,330 years to the present. We conducted two model runs to simulate the long-term accretion record starting at 3,300 years before present (Figures 7-9). Before 3,300 years, there was substantial variation in bulk density and organic matter content. In an effort to simplify the model development and accretion simulation and still gain understanding of Holocene accretion processes, we limited our analysis to the period after 3,300 years before present. During the recent-time simulation, we simulated accretion and the increased mineral input and associated bulk density in the last 150 years.

For the 3,330-year simulation, we used varying inputs shown in Table 3. We used an initial porosity value of 93% based on core data. The final porosity of 82 % was calibrated to match the bulk density data. Consistent with the literature for tidal wetlands described above, the organic matter input was constant at 0.06 g/cm^2-year. Sediment input (minin) of 0.08 g/cm^2-year was based on the titanium data. The average sediment input calculated from the titanium data (see Appendix B) was 0.07 g/cm^2-year.for core samples with age dates from 563 to 3524 years before present.

Consistent with relatively quiescent accretion during recent geologic time since about 2,100 years before present, bulk density and fraction organic matter content were relatively constant with elevation from about 0 to -200 cm ranging from 0.112 to 0.196 g/cm^3 and 0.48 to 0.74, respectively. However, most organic matter content values ranged from 0.59 to 0.74. Throughout the 3,330-year simulation, bulk density varied from 0.112 to 0.41 g/cm^3 and organic matter content fraction ranged from 0.22 to 0.74. At about 2,100 years before present, Browns Island experienced a large influx of sediment and measured bulk densities increased from 0.13 to 0.41 at elevations below -202 cm. Organic matter fractions decreased to 0.22. The average accretion rate during this 3,330-year period was 0.11 cm/year.

The simulation results for the upper 50 cm, which correspond to the past 150 years, are higher than older parts of the core, because sediment input and bulk density increased during this period, resulting in an average accretion rate of 0.3 cm/year. During this same period, bulk density values ranged from 0.109 to 0.38 g/cm^2. Also, subsidence due to gas withdrawal began within the last 80 years which we simulated as ranging from 0.05 to 0.11 cm/year based on core ^{137}Cs data and gas production information described in Appendix A. We estimated the sediment input from core titanium data (Appendix B). The average inorganic sediment input calculated from the titanium data was 0.041 g/cm^2-year for materials deposited approximately 174 calibrated years before present (1950) based on radiocarbon data. From 3,330 years to the present, the average estimated inorganic sediment input calculated from titanium data was 0.036, which was equal to the average model input.

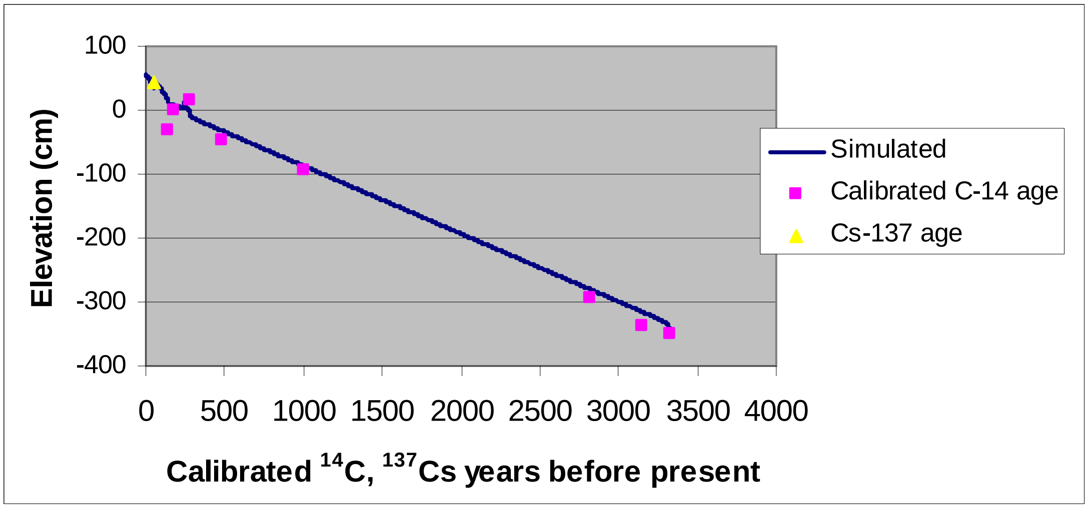

Figure 7. Simulated and calibrated accretion for Browns Island during the last 3,330 years. Elevation is relative to mean sea level.

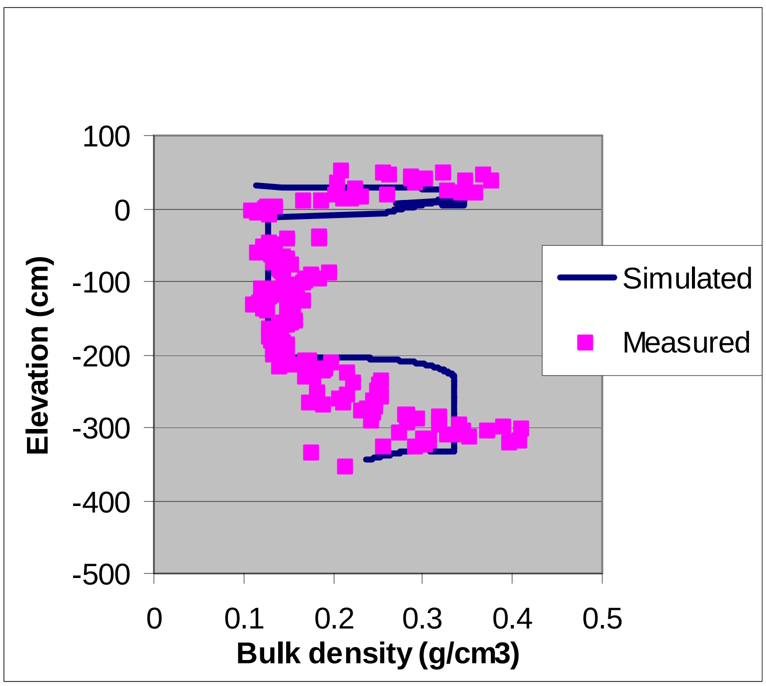

Figure 8. Measured and simulated bulk density for Browns Island. Elevation is relative to mean sea level.

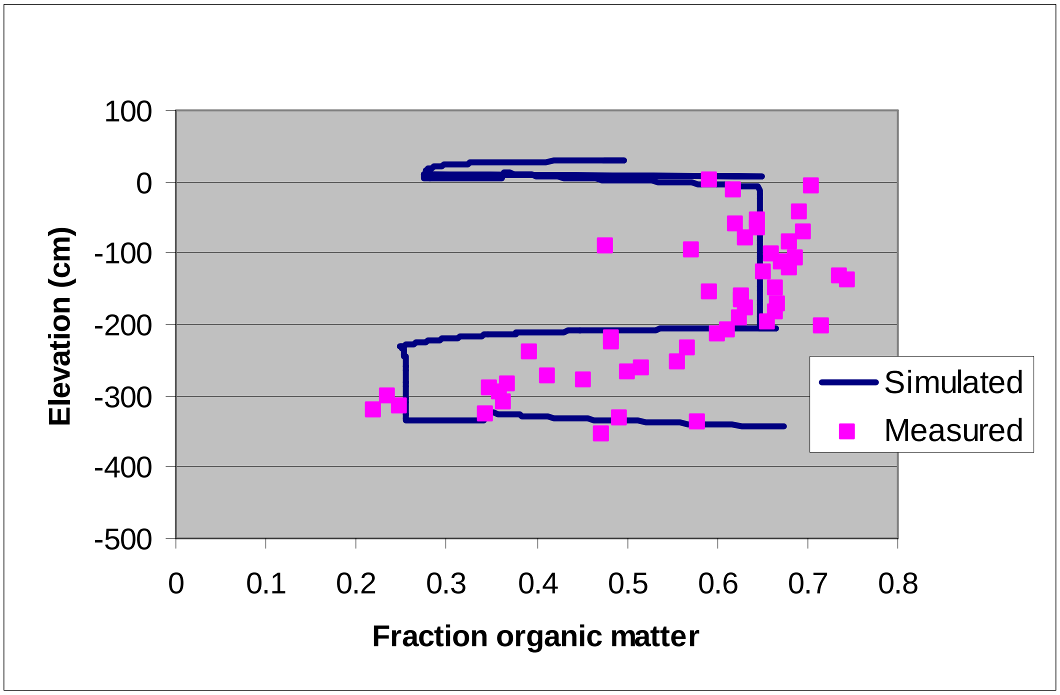

Figure 9. Simulated and measured organic matter content for Browns Island. Elevation is relative to mean sea level.

Twitchell Impounded Marsh Simulation Results

For Twitchell Island impounded marsh, we simulated accretion and compared model results with sedimentation erosion table (SET), bulk density and organic matter content measurements for the east and west ponds which are managed under different water depths; 25 cm in the west pond and 55 cm in the east pond. Figure 10 shows the simulation results for elevation change for the west and east ponds, respectively. Elevation increased in the west pond faster than in the east pond prior to 2003. Large elevation increases were measured in the east pond after 2003 whereas rates of elevation increases in west pond remained relatively stable. The 12 years of simulation and measured elevation increases show temporally variable conditions associated with marsh initiation. Accretion progressed slowly initially in the east pond at about 1.7 cm/year. During 2003 through 2009, rates increased substantially to over 7 cm/year between 2003 and 2005 and 5.7 cm/year between 2005 and 2008. The western pond showed more constant rates of elevation increase over time of about 3 cm/year.

Figure 11 and Table 4 show the comparison of measured and simulated elevation changes, bulk density, and organic matter content. There is generally good agreement between simulated and measured values for all three variables. Only four median values, two from each pond were available for bulk density and organic matter content for the material accreted since 1997. Bulk densities in the west pond and bulk density increased with depth. Lower bulk density values were measured in the east pond where water depths were maintained deeper. Consistently, core samples from the west pond had lower organic matter contents and organic matter content decreased with depth.

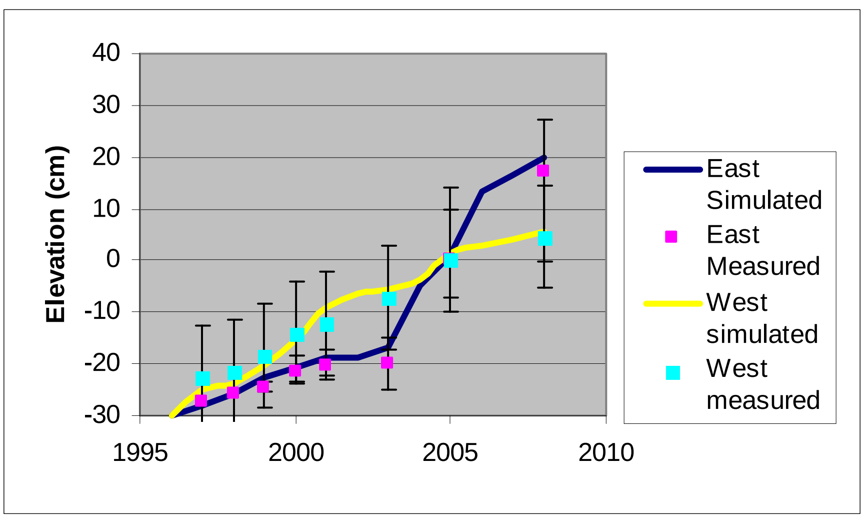

Figure 10. Simulated and measured accretion for Twitchell Island. Elevation values are relative to an arbitrary datum. The error bars for elevation measured with the SET show the standard error as provided by the US Geological Survey (Robin Miller, written communication, USGSCSWC, Sacramento, CA, 2008).

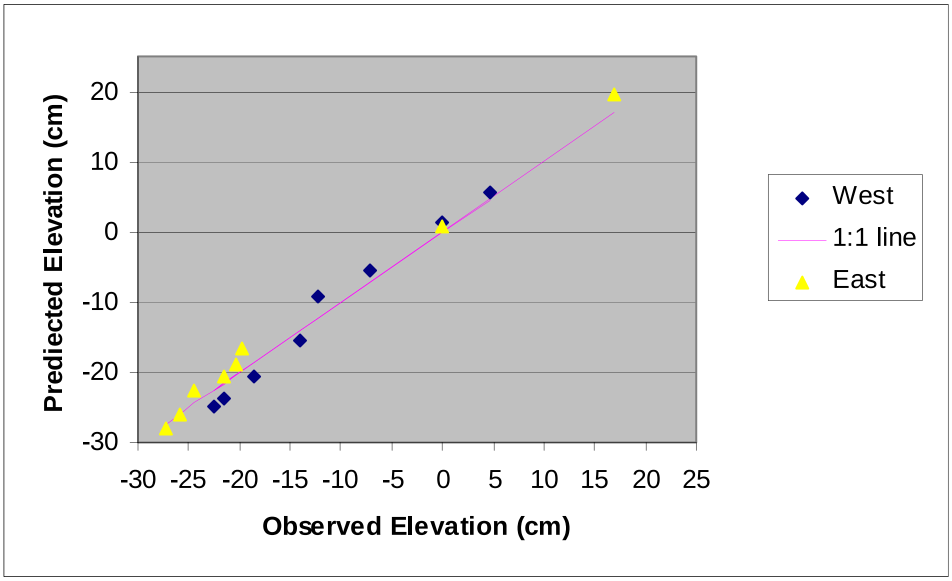

Figure 11. Predicted versus observed elevation for Twitchell Island. Elevation values are relative to an arbitrary datum.

Table 4. Measured and predicted organic matter fraction and bulk density.

Location and elevation	**Depth Interval (cm)**	**Predicted bulk density (g/cm^3)**	**Measured median bulk density (g/cm^3)**	**Predicted organic matter content as a fraction**	**Measured organic matter content as a fraction**	**Number of samples**
West pond	0-15	0.16	0.06	0.75	0.78	11
West pond	15-25	0.23	0.26	0.36	0.42	7
East pond	0-15	0.05	0.03	0.97	0.92	15
East pond	15-25	0.06	0.05	0.85	0.89	7

There are significant differences in input variables between the east and west pond simulations (Table 3). Because of the shallow water levels and apparent higher sediment input, initial and final porosity were lower and mineral input was larger for the west pond.

To estimate sediment inputs for the ponds we used flow and suspended solids data collected by the US Geological Survey (Gamble et al, 2003, Miller et al, 2008, Jacob Fleck, USGSCWSC, Sacramento, CA, written communication, 2006) for 1997 – 2001. This resulted in an average sediment input to both impounded marsh ponds of 0.03 g/cm^2-year. However, we varied the model sediment input relative to this average value to fit the bulk density and organic matter content of the cores as at least two factors have affected sediment input to the ponds over time. First, flow and sediment into the ponds varied over time and using a reasonable range of values provided by the US Geological Survey for flow and suspended sediment values, sediment input could have varied from 0.01 to 0.07 g/cm^2-year. Second, as plants grew, and the marsh developed, there was perturbation and probable uplifting by plants of the original organic soil below the material that is currently accumulating in the impounded marsh. This peat soil has a lower organic matter content of 18 to 24 % (Fleck et al., 2004) than the accumulating material in the impounded marsh. Vegetation was denser in the west pond which probably resulted in more uplifting of the underlying organic soil during early years. We therefore adjusted the sediment input upwards to as high as 0.2 g/ cm^2-year during the early simulation years to account for these effects. This variation in sediment input probably accounts for our inability to effectively match the median bulk density value for the west pond Table 4).

For the model input for organic matter to the marsh ponds, we used values provided by the US Geological Survey from measurements of plant biomass (Miller et al, 2008 and personal communication, Robin Miller, USGSCWSC, Sacramento, California, 2008). There were lower organic inputs to the east pond relative to the west pond even though more accretion was observed in the east pond. This is apparently the result of lower decomposition rates and higher porosities in the east pond. Measured decomposition rates using decomposition bags varied over time and we used data provided by the US Geological Survey (personal communication, Robin Miller, USGSCWSC, Sacramento, California, 2008) to determine rate constants.

Successful simulation of the Twitchell wetlands inspired some confidence in our ability to predict how elevation will change under wetland conditions on subsided Delta islands. The material currently deposited in the wetland is not peat but rather a transitional material that will continue to change and consolidate into peat. Successful simulation of accretion on channel islands provided insight about processes affecting accret6ion during several hundred years and provided further basis for prediction of future elevation increases in impounded marshes for subsidence mitigation which is discussed in the next section.

Future simulations

Impounded Marshes on Subsided Islands

There is substantial interest in stopping and reversing the effects of subsidence on Delta islands. Deverel et al. (1998), Miller et al. (2000), Miller et al. (2008) and Miller and Fujii (2008) have clearly demonstrated the potential for impounded marshes on Delta peat soils to result in a net carbon accumulation and reverse the effects of subsidence. Questions remain about the length of time to reach tidal range, especially in the western Delta. We therefore initially used the models developed for the Twitchell Island impounded marsh to estimate the time required to reach current sea level on the center of Twitchell Island which is about 630 cm below current sea level. Using the west and east pond models with the inputs from the most recent 4 years, our most probable estimates are 300 and 200 years after initial flooding for the west and east cells, respectively. We used the model inputs for the most recent 4 years because this period represented the most likely inorganic and organic inputs to the future marsh. Specifically, data indicated relatively stable organic inputs. Because of the shorter time estimate and faster measured accretion for the east pond wetland areas, we performed additional future simulations using the input parameters for the east pond.

The key uncertainty in estimating future elevation change is the extent to which the column of accumulating sediment will consolidate as it transforms from the loose and highly porous material collected from the Twitchell Island impounded marsh to the more decomposed and consolidated peat observed in the cores from the channel marsh islands and Twitchell Island (see Appendix E). There will be some consolidation as organic material continues to decompose, particles rearrange and pore space decreases. The key model variables affecting the rate and extent of consolidation are k_{cons} (described above in equation 2 which controls the rate at which the deposited material consolidates) and porelim, the limiting porosity. The initial porosity was set to 97 % based on the simulation of the Twitchell east pond data.

Because Franks Wetland probably represents physical conditions most similar to those for an impounded marsh (low-sediment input and quiescent conditions), the simulations provided some insight into the behavior of the accreting wetland materials and values for the consolidation variables (initial and final porosities, h2oin and porelim, and k_{cons}) for simulation of future conditions. We used Franks Wetland bulk density and loss-on-ignition (LOI) data to estimate the porosity inputs. The mean bulk density of 0.08 g/cm^3 measured in the Franks Wetland core results in a porosity of 0.94 using the equation 3.

$$\text{(Porosity = 1 – bulk density/particle density)} \qquad (3)$$

We estimated the particle density as equal to loss on ignition (LOI) x 1.14 g/cm^3 + (1-LOI) x 2.61 g/cm^3. The values of 1.14 and 2.61 g/cm^3 are the particle densities for organic and mineral fractions, respectively (DeLaune et al, 1983). Using the average bulk density of 0.03 g/cm^3 measured for recently accreted material in the Twitchell Island east pond and the measured mean LOI of 92 % results in a porosity of 97.6%. This was also the initial input for porosity (h2oin) for the Twitchell Island east pond simulation. Also, based on the results of using equation 3 using the average bulk density of Franks Wetland, we set the value of the final porosity (porelim) to 94% for the future simulation. For k_{cons}, we used a value of 10 which is consistent with Franks Wetland Holocene simulation and analysis of consolidation in the Twitchell Island mesocosms discussed in Appendix C.

The largest uncertainty in the future simulation is the extent of consolidation as the model output for elevation is highly sensitive to input porosities and k_{cons} (Calloway et al., 1996). By performing multiple simulations, we used the model to explore the effects of varying the values of variables affecting consolidation to ascertain the probable uncertainty in our estimates for rates of and the total time required to reach current sea level. Figures 12 and 13 and Table 6 show the results of these simulations which provide uncertainty estimates for future calculations. For this comparison, we have used time to reach current sea level.

Our analysis indicates that the uncertainty in our estimates for future accretion is plus or minus 60 to 100 years based on results using variations in porelim and the consolidation rate constant, k_{cons}. Specifically, using a k value of 250 (a maximum value used by Callaway et al, (1996) to simulate accretion in a Mississippi tidal marsh) and porelim value of 0.94 resulted in 106 years to reach current sea level. Using a porelim value of 0.925 which is more consistent with the Twitchell Island simulation through 2008 and a k_{cons} value of 10, resulted in a 257 year estimate to reach current sea level. Using a k_{cons} value of 100 with this porelim value resulted in 156 years to reach current sea level (Table 6, Figures 12 and 13).

Figure 13 shows trajectories for increases in elevation per year for the different simulations. In all cases, model results indicate varying degrees of slowing future accretion rates and that accretion rates have peaked and will decrease during future decades. Data provided by US Geological Survey (Robin Miller, USGSCWSC, Sacramento, CA, September 23, 2008, written communication) provide some support for this as they indicate that the rate of SET elevation increase decreased from 7.4 cm/year from 2003 to 2005 to 5.4 cm/year from 2005 to 2008. For our most probable estimate of 202 years, the model indicates that rates will decline and level off at about 2.9 cm/year within about 40 years. Using a larger value for k_{cons} results in a slower accretion rate decline. Using a k_{cons} value of 250 results in a rate decline to about 5 cm/year within 100 years and an estimated 106 years to reach current sea level. Using the lower porelim value of 92.5 % results in declining rates to 3.3 and 2.2 within 100 and 40 years and 117 and 257-year estimates to reach sea level for k_{cons} values of 250 and 10, respectively. For all simulations, we assumed low mineral input consistent with measured input values for the Twitchell Island impounded marsh. Our calculations indicate that the accreted material will be over 95 % organic material and have a bulk density of less that 0.1 g/cm^3.

Table 6. Values of k_{cons} and porelim and years to reach current sea level for model simulations shown in Figures 12 and 13.

Simulation number	k_{cons} value	porelim (as a fraction)	Years to reach current sea level on Twitchell Island
11	10	0.94	202
12	100	0.94	130
13	100	0.925	156
14	10	0.925	257
15	250	0.94	106
16	250	0.925	117

We used a GIS process, the simulation model estimates and LIDAR data for the Delta to develop a distribution of times for reaching sea level. We used estimates from Meehl et al. (2007), which provided global sea level rise projections to the end of the 21st century based on six scenarios. We used the projection based on the average of the two intermediate sea level rise projections; 0.395 cm/yr. In many portions of the Delta, land surface rise to sea level would take considerably longer than 100 years, which required sea level rise projection beyond that provided by Meehl, et al. (2007). We assumed that the 21st century projected sea level rise rate would continue indefinitely through the end of the time period represented on the map. To reflect projected accretion in relation to sea level rise on the map (Figure 14), we categorized the pixels of elevation data into 50-year intervals of elevation within the area of organic soils as delineated by Atwater (1980).

If flooded and managed as impounded marshes, our results indicate that large areas of subsided islands in the periphery of the Delta as well as other islands could be restored to sea level within 50 to 100 years, (Figure 14). The blue, green, and yellow areas on Figure 14 include large areas of Ryer, Grand, Tyler and Staten islands and areas in the southwestern, northern, eastern and southeastern Delta. The model results indicate that most of the central Delta would require 150 to 250 years for restoration to sea level. There is heightened interest in potential accretion rates in the western Delta due to water supply and water-quality concerns associated with level failure. In the western Delta, Sherman Island is a highly vulnerable island due high potential for seismically induced levee failure and a large volume below sea level. Our calculations indicated that a large portion of the island could be restored to sea level within 50 to 150 years. Deeply subsided portions on the southwestern and southeastern parts of the island would require 150-200 years to reach sea level. Large portions of Jersey and Bethel islands could be restored to sea level within 51 -100 years. Small areas on Bradford, Twitchell, Brannan and Webb could be restored to sea level within 51-100 years, but most of these islands are deeply subsided and would require 150 - 250 years to restore to sea level. Model results indicate large areas of Ryer and Grand islands could be restored to sea level within 51 to 100 years.

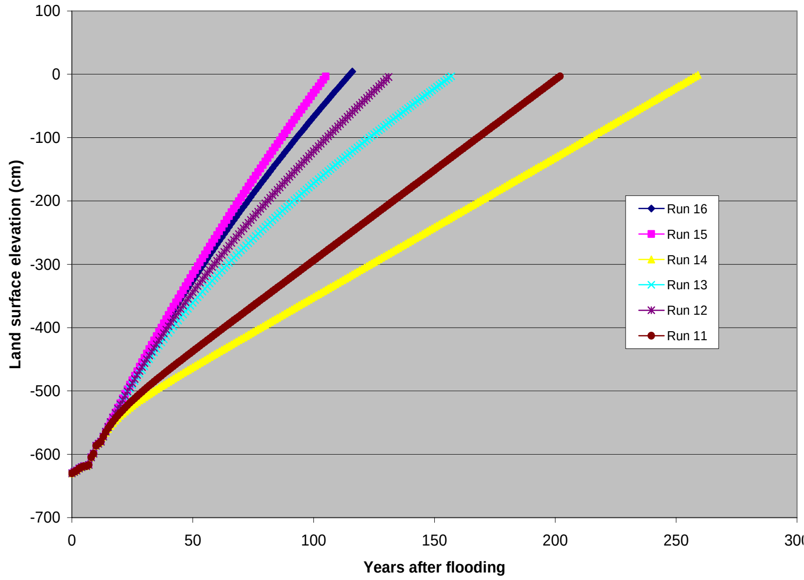

Figure 12. Model estimates for accretion to current sea level on Twitchell Island.

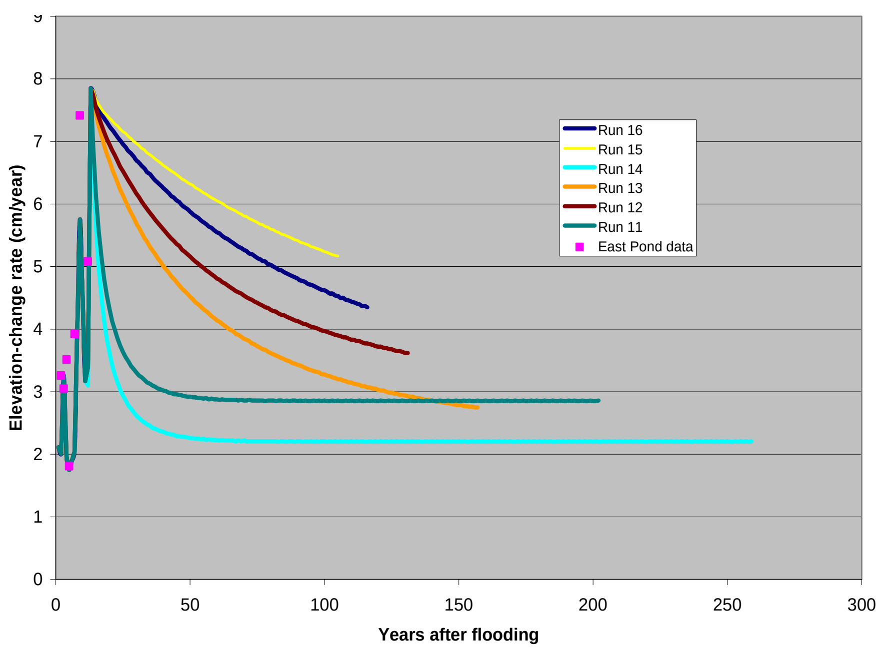

Figure 13. Model estimated and measured accretion rates for Twitchell impounded marsh, east pond.

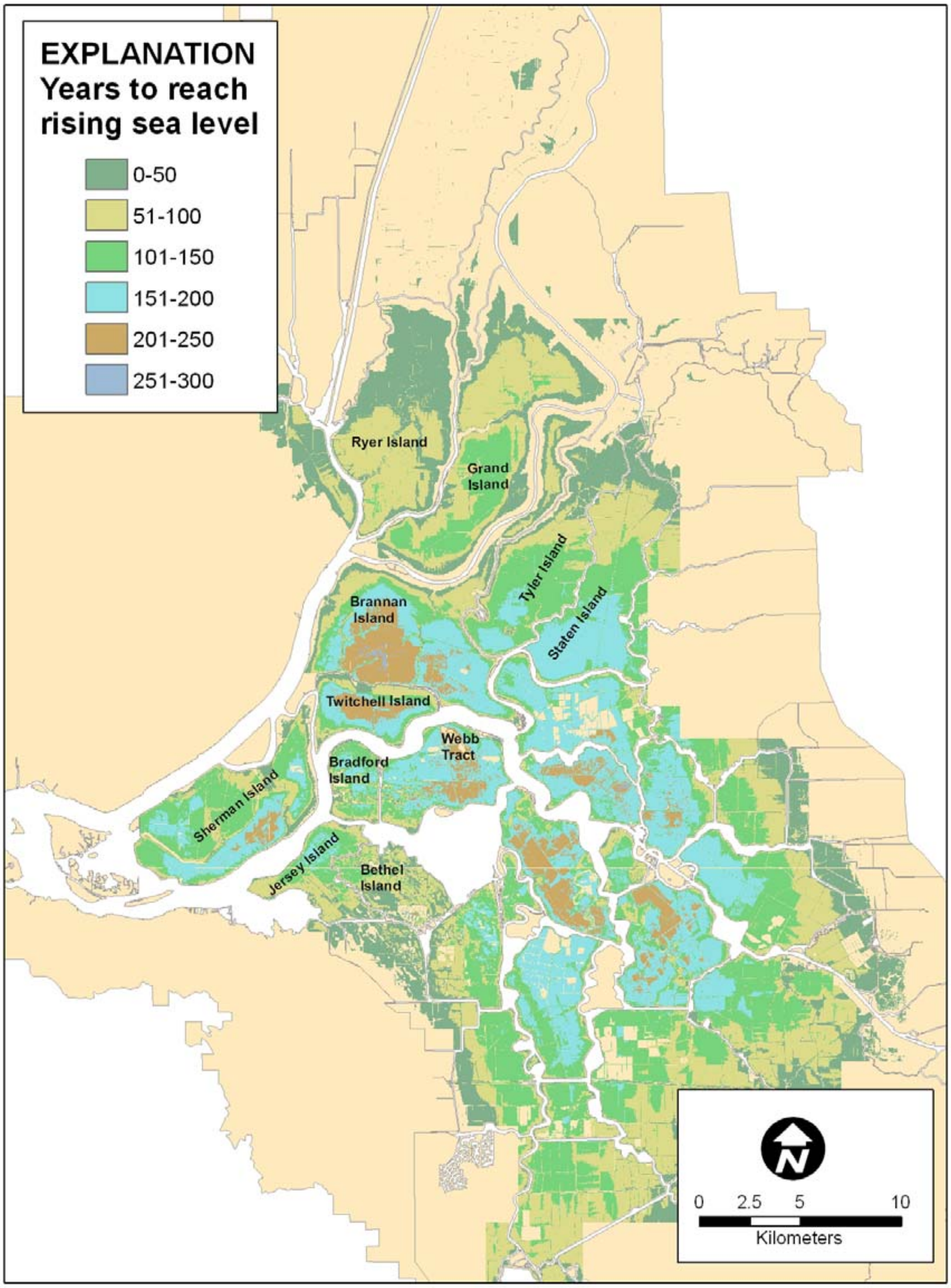

Figure 14. Distribution of estimates for subsided islands to reach projected sea level in the Delta.

Channel Marsh Islands

We addressed the question of how Franks Wetland and Browns Island will accrete relative to three possible sea level rise scenarios to 2050 and 2100. Orr et al. (2003) indicated that as sea level rises, sediment concentrations will decrease. For future simulations of effects of sea level rise on tidal wetlands in San Pablo Bay, they estimated that suspended sediment concentrations could decrease by one half. Therefore, we simulated future accretion on Franks Wetland and Browns Island with three levels of sea level rise (0.17, 0.395 and 0.78 cm/year as indicated by Meehl, et al. (2007) and 100 and 50 % of sediment input levels shown in Table 3 for the recent simulations on these islands (0.044 and 0.022 and 0.05 and 0.025 g/cm^2-year for Browns and Franks Wetland, respectively). Simulation results indicate that for both sediment input levels on Browns Island, the 2050 elevation will be greater than the projected sea level at the highest rate of rise. In 2100, our model results indicate that Browns Island would continue to maintain sufficient accretion rates and remain emergent at the highest rate of sea level rise. For Franks Wetland elevation would increase to about 16 cm, about 3 cm less than the projected sea level rise at 0.395 cm/year in 2050. We predict that Franks Wetland would become submerged and unable to accrete sufficiently to continue to exist at the highest rate sea level rise. In 100 years, Franks Wetland would be unable to maintain sufficient elevation to survive at the intermediate rate of sea level rise.

DISCUSSION

Our Delta analysis of accretion provides unique insights about temporally and spatially variable processes affecting accretion and predictions of future marsh development in the Delta. In contrast to previous modeling efforts, the efforts described here are more holistic in that inorganic sediment and organic inputs are accounted for in more detail. Moreover, this project and the research at the Twitchell Island impounded marsh provided extensive data for model development and calibration. Simulation of accretion of tidal wetlands on Browns Island and Franks Wetland provided insight into probable future accretion for impounded marshes and the appropriate model inputs for simulation of consolidation.

Details of the individual simulations discussed above reveal good agreement between simulated and measured accretion rates, bulk density and organic matter content. Accretion during the last 4,700 years can be characterized as driven by relatively low mineral and organic inputs in response to sea level rise of about 0.17 cm/year. Franks Wetland and Browns Island represent different hydrologic dynamics. Franks Wetland apparently accreted under relatively quiet low-mineral-input conditions when contrasted to the larger sediment inputs associated with the apparently more fluvial influence for the Browns Island accretion (Drexler et al., 2009b). Accretion within the last several hundred years on both islands has been subject to more mineral input than during the past several thousand years. Within the past 80 years, there has been land-surface subsidence due to gas withdrawal.

In contrast to the two channel marsh islands where there have been varying degrees of surface perturbations and accretion has been driven by sea level rise, Twitchell Island represents an impounded managed hydrologic environment which facilitates greater organic accumulation and faster accretion. However, data and accretion simulation for Browns and Franks Wetland provided insight about model inputs for the Twitchell Island simulations and how these wetlands may accrete in the future. We therefore predicted future accretion for the Twitchell Island impounded marsh and extrapolated these results to other subsided islands to estimate trajectories for accretion to reach projected sea levels. We also assessed accretion rates on natural tidal marshes relative to anticipated sea-level rise.

Four variables standout as key to effective simulation of accretion in the varied Delta environments: inorganic and organic inputs, porosity and control of the rate of consolidation. The primary unknowns varied for the three locations. Core data provided bounds for porosity inputs and data for the Twitchell impounded marsh provided input data for inorganic and organic inputs. The key unknown that requires further investigation is the extent and rates of consolidation. Our approach of using data from the Twitchell mesocosms provided some confidence in the values of k_{cons}. However, model results are highly sensitive to the porosity and k_{cons} values as was demonstrated by the future simulations for the Twitchell Island impounded marsh using a range of literature-cited values. Small to moderate changes in the final porosity inputs and the consolidation constants substantially change future accretion estimates.

That there will be future consolidation of deposited organic and inorganic sediments appears obvious from the literature on the subject and the data for the different islands. Clearly, mineral deposition has resulted in increased bulk density of the accreted material on Browns Island and Franks Wetland. While the mechanisms of consolidation of highly organic deposits has not been fully quantified, two processes lead to consolidation; decomposition of organic detritus which results in structural rearrangement of organic particles, and a concomitant reduction of pore space, which results in expulsion of water (Hobbs, 1986). Therefore, the extent of consolidation of primarily organic deposits or change in void ratio (volume of water and air relative to the volume of solids) is a function of the effective stress (a function of buoyant support and weight of the deposits) (e.g., Pizzulo and Swendt (1997). Pizzulo and Swendt (1997) estimated consolidation rates in peat deposits in Delaware of about 1 mm/year during the last 6,000 years. Also, Tornqvist et al. (2008) estimated consolidation rates of 5 mm/year in highly organic Holocene deposits in the Mississippi Delta.

There has been little previous attention to regional Delta subsidence due to gas withdrawal and effects on wetland accretion and Delta elevations. We utilized the available data to incorporate this process into our model. Our analysis indicates that it has been a significant process during the last 80 years resulting in 0.1 to 0.5 cm/year of regional subsidence and needs to be included in future estimates of Delta elevation changes. The possible effects of recent proliferation of new gas wells on western Delta islands warrant further investigation. Results of modeling accretion in the face of regional subsidence on Franks Wetland and Browns Island indicate that wetlands have compensated for past subsidence through more sediment and organic-matter accumulation. There is some evidence in the literature for similar responses in other locations. For example, Atwater et al. (2001) and Cahoon and Lynch (1997) presented evidence for wetland accretion in response to sudden and gradual subsidence. Baldwin and Mendelssohn (1997) provided evidence for increased biomass (including *Schoenoplectus tabernaemontani*) production in response to flooding and marsh disturbance. It appears likely that in response to the onset of subsidence and periodic disturbance on channel marsh islands, sediment deposition increased which probably coincided with increased biomass production.

SUMMARY AND CONCLUSIONS

As part of a study on peat accretion processes in the Sacramento-San Joaquin Delta, we attempted to simulate wetland accretion on three islands; Franks Wetland, Browns Island, and the Twitchell Island demonstration wetlands. We modified the cohort-accounting model of Callaway et al. (1996) to accept yearly inputs for selected parameters and used physical and chemical data collected during the course of the study and the literature to develop model input files. For Franks Wetland and Browns Island, we simulated Holocene accretion since about 4,000 years before present using ^{14}C data for comparison with simulated accretion rates. We also simulated recent accretion and compared our results with ^{210}Pb and ^{137}Cs data. For the Twitchell Island impounded marsh, we compared our results with sedimentation-erosion table results and core data collected by the USGSCWSC from 1997 to 2008. For all three islands, we were able to successfully simulate accretion and our results compared favorably with measured core bulk density and organic matter content.

Accretion on all three islands can be generally characterized as being dominated by organic inputs and high porosities with varying degrees of sediment input depending on the hydrogeomorphic setting. Franks Wetland and Browns Island represent hydrogeomorphically different systems due to their positions in the Delta. Accretion rates on both islands were about 0.1 cm/year consistent with accretion rates in tidal wetlands worldwide. Franks Island is in a less dynamic location and received relatively little sediment from 4,650 to 425 years before present (1950). Browns Island received larger sediment input than Franks Wetland by over an order of magnitude. Browns Island also experienced large episodic sediment influxes during the Holocene. During the Holocene, both islands experienced comparable organic inputs consistent with the literature for tidal marshes. Recent simulations indicated large sediment inputs on both islands during the last 150 to 200 years which resulted in larger accretion rates of 0.3 to 0.4 cm/year due to sediment influxes to the Delta from hydraulic mining.

The Twitchell Island impounded marshes, a demonstration project for subsidence mitigation, functions differently from the channel marsh islands. All organic and inorganic inputs stay in the confines of the marsh. This has resulted in greater organic inputs and average accretion rates as high as 7.4 cm/year. Future simulations for the three islands indicate that managed impounded marshes such as the Twitchell Island project will probably accrete highly organic (over 90 %), low bulk density material at rates of about 3 cm/year. The primary uncertainty in future estimates is how porosties will change. The uncertainty in future accretion rates ranges is approximately +/- 1 to 2 cm/year. The key unanswered question is how the currently developing materials observed on Twitchell Island will transform and porosity will change as material accumulates in the wetland.

Extension of the results to other Delta islands indicates that large areas of the periphery of the Delta could be restored to tidal elevations within 50 to 100 years (large areas of Ryer, Grand, Tyler and Staten islands and areas in the southwestern Delta) by creating impounded wetlands. Most of the central Delta would require 50 to 200 years to be restored to seal level in such a fashion. A large portion of the western Delta could be restored to sea level within 50 to 150 years (large areas on Sherman Island, Jersey and Bethel islands and small areas on Bradford, Twitchell, Brannan and Webb).

APPENDIX A. SUBSIDENCE DUE TO NATURAL GAS WITHDRAWAL

Many natural gas fields have been developed in the Delta. Rojstaczer et al. (1991) showed the locations of the major gas extraction areas in the Rio Vista Gas Field that are adjacent to and in the Delta as underlying Twitchell, Bradford, Ryer, Staten, Jersey and Bethel islands. The Rio Vista Gas Field is the largest gas field in California and has been under production since 1936. The reservoir rocks are Upper Cretaceous to Eocene and consist of alternating layers of sands and shales deposited in deltaic and marine environments. Gas withdrawal occurs at 1,150 to 1,310 m in an average thickness of 15 to 100 m. Production peaked in 1951 and declined steadily since then (Cummings, 1999). Production decline resulted from decreasing reservoir pressures and increased water production, particularly on the western boundary of the field. Rojstaczer et al. (1991) reviewed California Division of Oil and Gas records in the late 1980's and stated that pressures had declined 2,000 pounds per square inch since 1945.

Significant compaction of the rocks in the gas field could occur if the gas reservoirs are sufficiently depressurized (California Department of Water Resources, 1980), resulting in elevation loss. Gas withdrawal has resulted in significant subsidence other locations. Martin and Serdengecti (1984) reported that subsidence associated with gas withdrawal is relatively rare but factors related to reservoir geometry and rock properties can result in significant compaction of gas reservoirs with decreasing pressure. In their review, Martin and Serdengecti (1984) found that large stress-transfer factors that result in subsidence occur in relatively shallow, thin and areally extensive reservoirs. The characteristics of the Rio Vista Gas Field are consistent with large stress-transfer factors; 1,200 m deep (90% of gas reservoirs are deeper than this), about 60-m thick and about 12 km in diameter (Rojstaczer et al, 1991; Oldenburg et al, 2001). Martin and Serdengecti (1984) also found that the majority of compaction in gas fields occurred in sands.

Subsidence was estimated from ^{137}Cs and ^{210}Pb data for sediment cores collected during this study and by Rojstaczer et al. (1991) and gas production and pressure data. We varied the amount of subsidence as a yearly input to account for the varying subsidence due to varying pressures in the Rio Vista Gas Field. As discussed in the introduction, data collected by Rojstaczer et al. (1991) indicated regional subsidence rates ranging from 0.35 to 0.54 cm/year due to gas and groundwater withdrawal from 1963 to 1989. In the ^{137}Cs data collected in the Browns Island core during this study the1963 peak was measured at 13.1 cm below the top of the core indicating an accretion rate of 0.31 cm/year. Assuming 0.17 cm/year of sea level rise we estimated an average of 0.14 cm/year of subsidence from 1963 to 2008. Analysis of the gas pressure and production data for the Rio Vista Gas Field points to changing subsidence rates over time. We therefore developed yearly estimates for subsidence rates starting in the 1930's. We recognize that accretion does not strictly occur concomitantly with sea level rise. However, given the limited data for accretion, we assumed for modeling purposes that the difference between total accretion and sea level rise was due to subsidence.

For the Franks Wetland simulations we used ^{210}Pb data to estimate an average subsidence rate of 0.28 cm/year from 1930 to 2006 (Figure 4). Specifically, for each depth interval bracketed by ^{210}Pb data, we estimated the subsidence rate assuming a 0.17 cm/year rate of sea level rise. Figure 4 shows that the subsidence rate varied over time, reached a peak in the 1960's and then declined. We used the two exponential functions shown in Figure A1 to estimate the yearly subsidence rate in the model. For the Browns Island simulation we assumed that subsidence increased in the late 1930's and early 1940's and reached a maximum in 1962 and then declined exponentially to result in an average subsidence rate from 1963 to 2008 equal to the rate indicated by the ^{137}Cs data.

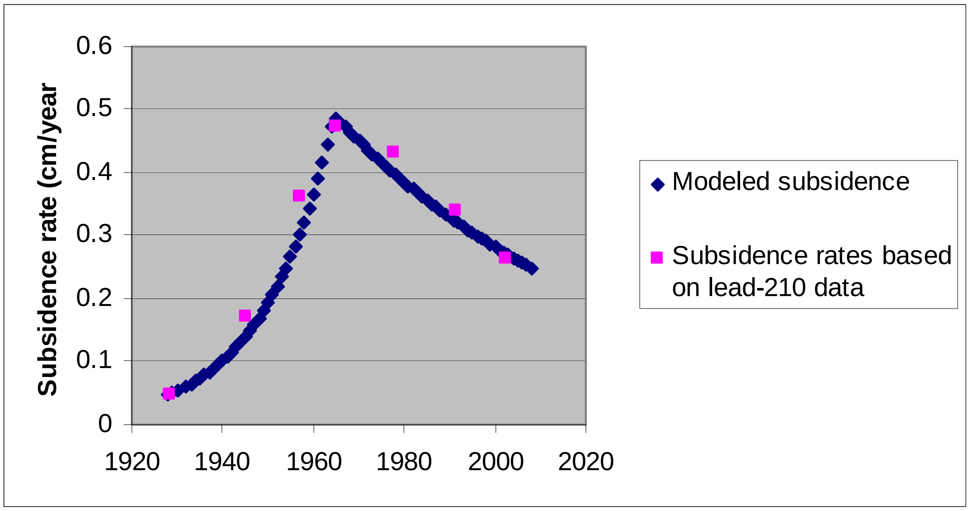

Figure A1. Estimated subsidence rate due to gas withdrawal for Franks Wetland simulation.

APPENDIX B. USE OF TITANIUM DATA TO ESTIMATE CORE INORGANIC INPUTS

We used titanium data for cores collected on Browns Island and Franks Wetland to estimate temporally variable inorganic inputs for the model as titanium does not bioaccumulate in plant tissue or organic matter (Pendias and Pendias, 1992). Figure B.1 shows a linear relation for %Ti plotted vs. %LOI and the intercept is 0.5308 % Ti for a hypothetical LOI of 0 %. We identified a similar linear relation for the Franks Wetland data with an intercept of 0.36 %. We assumed the values of 0.36 and 0.53 % represent end members for the pure inorganic sediment. For each depth sample where there was both Ti and bulk density, we divided each sample %Ti value by 0.53 to estimate the fraction of the sample that is inorganic sediment. Then, we multiplied this quotient by the bulk density to estimate the grams inorganic sediment per cm^3. For the depth interval between age dates, we multiplied the average of the sample inorganic sediment times the depth interval to obtain the average amount of inorganic sediment per unit area in g/cm^2. We then divided this number by the age difference to obtain the rate of sediment accumulation in g/cm^2-year.

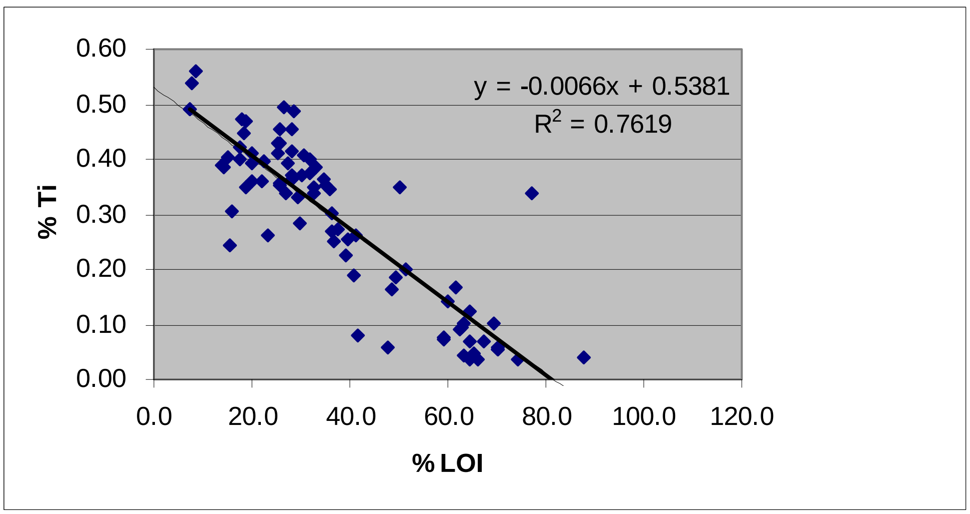

Figure B1. Relation of percent titanium in core samples and % LOI.

APPENDIX C. ESTIMATION OF CONSOLIDATION CONSTANT USING TWITCHELL ISLAND MESOCOSM DATA

Prompted by the practice of broadcasting thin layers of sediment from channels on adjacent wetlands in the eastern United States, HydroFocus, Inc. (HydroFocus, 2007) conducted a study of the application of thin layers of mineral sediments to enhance wetland accretion rates and hasten achievement of land-surface elevation increases on deeply subsided islands. The primary objective of the study was to evaluate the potential use of thin-layer sediment application for enhancing accretion rates. We applied sediment to experimental wetland mesocosms in 2006 on Twitchell Island where *Schoenoplectus americanas* grew from 2002 to 2006. We measured biomass, rates of accretion and elevation change and bulk density and evaluated changes in these before and after sediment application. We placed feldspar markers for subsequent accretion measurements as described by Rejmaneck et al. (1988). Using a coring device similar to that described in Hargis and Twilley (1994), we collected cores in February and March 2006 (before sediment application) and during August and December 2006 (after sediment application). We determined the depth of accumulated sediment above the feldspar marker by extruding the sediment core and measuring the depth of sediment accumulated above the marker. In the collected cores, we determined bulk density by sectioning a portion of the core and following methods described in Blake and Hartge (1986).

We used the model developed by Calloway and others (1996) to simulate recent accretion in the mesocosms. First, we used the model to simulate accretion in the mesocosms ponds from 2002 to 2005.using known inputs for the mesocosms and ancillary data for the Twitchell Island impounded wetland. The model performed reasonably well in simulating accretion and bulk density in the mesocosms, the average increase in elevation measured with SET was 1.0 cm/year and values ranged from 0.43 to 2.7 cm/year. The average model predicted elevation increase was 0.9 cm/year. To estimate the model consolidation constant, k_{cons}, we simulated accretion before (2002 – 2005) and after sediment application of 5 cm in March 2006. The median bulk density values were 0.38 and 0.56 g/cm^3, before and after application, respectively, indicating a 48 % increase. We varied the value of k_{cons} to simulate this increase in bulk density. We also varied the inorganic input before sediment application due to measurement uncertainty. The most reasonable results were for k_{cons} = 3 to 10. This provided a starting place for the input of k_{cons} for the accretion model for Franks Wetland, Browns Island and the Twitchell Island impounded marsh.

APPENDIX D. RESULTS OF LITERATURE REVIEW FOR DECOMPOSITION CONSTANT

Table D1. Values of decomposition constant.

Source	*Species*	Wetlands Description		K_{decomp} (year^{-1})
Anderson and Smith, 2002.	*P. pensylvanicum*	Playa wetlands, south Texas. Mean annual precipitation 52 cm. K values were calculated for plant parts (leaf, stem, and seed). Summarized values are average of plant parts.	Flooded 30% of time	1.36
			Flooded 41% of time	1.87
			Flooded 58% of time	0.88
			Flooded 100% of time	0.47
Atkinson and Cairns, 2001.	*Schoenoplectus cyperinus*	Appalachian, contour mining depressions (20 years old) and experimental depressions (2 years old).	2-year old	0.11
			20-year old	0.22
	Typha latifolia		2-year old	0.37
			20-year old	0.29
Chimner and Ewel, 2005	*Terminalia carolinensis*	Tropical fresh-water wetlands	Leaves	3.66-5.24
			Branches	0.70-0.845
			Roots	0.58-1.064
Conner and Day, 1991.	water tupelo, ash, maple, bald cypress	Louisiana, subtropical, forested freshwater wetlands. Mean annual precipitation 160 cm; mean annual temperature 20.6˚C.	Crayfish pond, 40-50 cm deep in winter/spring, drained in April.	2.081
			impounded swamp	0.769
			unaltered swamp (natural overland flow)	0.832
Corstanje et al, 2006.	*Typha latifolia, Cladium jamaicense*	Florida campus, 3 14-sq-m-mesocosms	organic soil enriched with N and P	1.7
			organic soil, not enriched	1.1
			mineral soil, not enriched	0.81
			organic soil enriched with N and P	0.95
			organic soil, not enriched	0.98
			mineral soil,	0.38

			not enriched	
Davis and van der Valk, 1978.	*Typha glauca Schoenoplectus fluviatilis*	Goose Lake, Iowa. Prairie glacial marsh.	Standing plants	1.50
			Suspended litter	
			Submerged litter	
			Standing plants	1.17
			Suspended litter	
			Submerged litter	
Hietz, 1992.	*Phragmites australis*	Austria: 5 sites ranging from 3000 to 100 m from lakeside. Used coarse and fine litter bags. One site in reedless pool. Some suspended above water. Some litter transported to site other than that of origin.	site 1: 3000 m from open water	0.757
			site 2: 2200 m from open water	
			site 3: 1500 m from open water	
			site 4: 800 m from open water	
			site 5: 100 m from open water	1.125
Lee and Bukaveckas, 2002.	*Typha latifolia, Salix nigra, Caphalanthus occidentalis, Phragmites australis, Rumex crispus, Schoenoplectus cyperinus, Acer rubrum, Sagittaria brevirostra, Carex sp*	West Kentucky, subject to agricultural or coal runoff. Humid, continental climate.	Min	3.65
			Max	27.38
Lee, 1990.	*Phragmites communis*	Hong Kong tidal shrimp pond in nature reserve	"upper": most extreme temperature fluctuations and most immersion time	1.93815

			"middle"	1.0074
Windham, 2001.	*Phragmites australis*	Brackish tidal marsh, southern New Jersey		0.25
	P australis in S patens plot			0.24
	Spartina patens			0.57
Vargo et al, 1998.	*Typha latifolia T. angustifolia Sparganium eurycarpum*	Shallow wetland along shore of eutrophic lake, Michigan	no sediment added	0.77
			single sedimentation	0.66
			multiple sedimentation	0.62
			no sediment added	0.62
			unenriched sediment	0.58
			P-rich sediment	0.58
			no sediment added	0.73
			unenriched sediment	0.51
			P-rich sediment	0.47
USGSCWSC, personal communication 2007.	*Schoenoplectus*	Sacramento-San Joaquin Delta - 25-cm and 55-cm experimental wetlands		0.99-1.6
	Typha			0.55-1.2

APPENDIX E. PHOTOGRAPHS OF CORE SAMPLES FROM TWITCHELL ISLAND

Figure D1. Photograph of recently deposited material in the Twitchell Island impounded marsh. (Photo courtesy of Robin Miller, USGSCWSC, Sacramento, CA).

Figure D2. Photograph of core collected from about 3 m below land surface on Twitchell Island.

APPENDIX F. FORTRAN LISTING OF PROGRAM USED FOR ACCRETION SIMULATION FOR TWITCHELL ISLAND IMPOUNDED MARSH, EAST POND AND INPUT AND OUTPUT FILES

```
c this is sed5.for  -  sediment accretion program for fortran
c declaring variables
c
      real*8 org, min, orgden, minden, h2oden, pore, minin, orgin
      real*8 orgbd, minbd, bulkd, porg, depth, massabv, intelv, relelv
      real*8 slr, subsid, totorg, totvol, orgvol, minvol, densabv
      real*8 dt, mindev, porelim, refrac,h2oin
      real*8 pctpore, tpore
      real*8 acc1000, org1000, min1000, acc4000, org4000, min4000
      real*8 acc4900, org4900, min4900, finelv
      real*8 kdec1
      integer time, t2, endtim
      dimension org(0:7000,4), min(0:7000), pore(0:7000), totvol(7000)
      dimension orgbd(7000), minbd(7000), porg(7000), minvol(7000)
      dimension depth(0:7000),  massabv(0:7000), densabv(0:7000)
      dimension bulkd(7000),relelv(0:7000),totorg(0:7000),orgvol(7000)
      dimension pctpore(0:7000)
      dimension tpore(0:7000)
      dimension minin(7000)
      dimension orgin(7000)
      dimension h2oin(7000)
      dimension porelim(7000)
      dimension kdec1(7000)
c
c initializing values
c
      open (25, file = 'sksxx.dat', status = 'unknown')
c     open (26, file = 'orgac5dat', status = 'unknown')
      open (27, file = 'decmp1out.txt', status = 'unknown')
      open (28, file = 'decmp2out.txt', status = 'unknown')
      open (29, file = 'decmp3out.txt', status = 'unknown')
      open (10, file = 'minin.txt', status = 'old')
      open (11, file = 'orgin.txt', status = 'old')
      open (12, file = 'h2oin.txt', status = 'old')
      open (13, file = 'porelim.txt', status = 'old')
      open (14, file = 'decmpin.txt', status = 'old')
      open (15, file = 'fw_mininout.txt', status = 'unknown')
c     open (16, file = 'fw_orginout.txt', status = 'unknown')
      data totorg /7001*0.0/
      data min/7001*0.0/
      data pore/7001*0.0/
      data totvol/7000*0.0/
      data depth/7001*0.0/
      data massabv/7001*0.0/
      data densabv/7001*0.0/
      data relelv/7001*0/
      data pctpore/7001*0/
c     orgin = 0.0
c     minin = 0.0
c     h2oin = 0.96
      mindev = 0.0
```

```
      strint = 5.0
      strdev = 0.3
c     porelim = 0.925
      refrac = 0.2
c
c h20in is a percent.  It has to be converted to a volume
c to be useful for calculations.  The conversion from % to volume is:
c porespace volume = ((%)/(1-%))*(minvol + orgvol)
      orgden = 1.14
      minden = 2.61
      h2oden = 1.00
      intelv = -30
      slr = 0.0
      subsid = 0.0
      endtim = 13
c
c ************************************************
c this is the beginning of the main control loop *
c ************************************************
c
      do 100 time = 1, endtim
c
c this section moves all values down one section
c before the next round of growth, new input and decomposition
c
        do 10 t2 = time-1, 0, -1
          org(t2+1,4) = org(t2,4)
          org(t2+1,3) = org(t2,3) + org(t2,2)
          org(t2+1,2) = org(t2,1)
          org(t2+1,1) = 0.0
          min(t2+1) = min(t2)
c         pctpore(t2+1) = pctpore(t2)
          tpore(t2+1) = tpore(t2)
10      end do
c
c ************************************************************
c * these are the new inputs of material onto the surface of *
c * the marsh (into the first position in the array).        *
c ************************************************************
c
        READ (10,*) i, minin(time)
c       write (15,*) i, minin(time)
        read (11,*) j,orgin(time)
c       write(16,*) j, orgin(time)
        Read (12,*) k,h2oin(time)
        Read (13,*) l,porelim(time)
        read (14,*) m,kdec1(time)
C       minin(i)=minin(time)
C       orgin(j)=orgin(time)
        org(1,1) = orgin(j)*(1-refrac)
        org(1,4) = orgin(j)*refrac
        min(1) = (minin(i))*(rtemin(relelv(time-1)))
        write(15,*) rtemin(relelv),time
c
c
        tpore(1) = 1.00
        pctpore(1) = h2oin(1)
```

```
        pore(1) = ((h2oin(time)/(1-h2oin(time)))*((org(1,1)/
     &   orgden)+(min(1)/minden)))
c
c ******************************************************************
c * the following section is where the "yearly" calculations       *
c * take place.  It combines all of the other calculation sections *
c * from earlier versions of the model (7/10/93).                  *
c ******************************************************************
c
c this section calculates the volume of each section
c based on the mass of organic matter, mineral matter, and
c water.  It will also use a compaction subfunction in
c the future. Compaction will be a function of the
c mass that is on top of the current section.
c
c
c this is where the new roots and rhizomes are put into
c the sediment.  rtprod is a subroutine/function
c that will determine root production based on depth/time
c
c this is also the decomposition section.  Again decomp is
c a subroutine based on depth/time.
c
        do 20 t2 = 1, time
          istep = 10
          dt = 1.0/floatj(istep)
          do 19 ie = 1, istep
            totorg(t2) = org(t2,1)+org(t2,2)+org(t2,3)+org(t2,4)
            massabv(t2) = massabv((t2)-1)+totorg(t2-1)+min(t2-1)
     &       + pore(t2-1)
            if (depth(t2-1).eq.0) then
              densabv(t2) = 0
            else
              densabv(t2) = massabv(t2)/(depth(t2-1))
            end if
            orgvol(t2) = (totorg(t2)/orgden)
            minvol(t2) = (min(t2)/minden)
            if (t2.le.1) then
              pctpore(t2) = pctpore(t2)
            else
              dum1 = h2oin(time)
              dum2 = porelim(time)
              tpore(t2)=tpore(t2) - (tpore(t2) -
     &         tpore(t2)*(poresp(densabv(t2))))*dt
              pctpore(t2)=dum2+(dum1-dum2)*tpore(t2)
c             pctpore(t2)=porelim+(dum1-porelim)*tpore(t2)
c             write (6,999) tpore(t2), pctpore(t2)
            end if
            pore(t2) = ((pctpore(t2)/(1-pctpore(t2)))*(orgvol(t2) +
     &       minvol(t2)))
c           pore(t2) = h2oin
c the line above is for running the model without compaction
c pore space is constant for all sections.
c
            totvol(t2) = orgvol(t2) + minvol(t2) + pore(t2)
            depth(t2) = depth ((t2)-1) + totvol(t2)
            porg(t2) = totorg(t2)/(totorg(t2) + min(t2))
```

```
            bulkd(t2) = (totorg(t2)+min(t2))/totvol(t2)
            orgbd(t2) = totorg(t2)/totvol(t2)
            minbd(t2) = min(t2)/totvol(t2)
            org(t2,1) = org(t2,1)+((dt*(rtprod(depth(t2))*totvol(t2)))
     &       *(1-refrac))
     &       - ((dt*(((decmp1(depth(t2),kdec1(time)))*org(t2,1)))))
            org(t2,2) = org(t2,2)
     &       - (dt*(((decmp2(depth(t2)))*org(t2,2))))
            org(t2,3) = org(t2,3)
     &       - (dt*(((decmp3(depth(t2)))*org(t2,3))))
            org(t2,4) = org(t2,4)+((dt*(rtprod(depth(t2))*totvol(t2)))
     &       *refrac)
c
c commenting out the 3 "&" lines above, cuts out decompostion
c
c           write(29,*) decmp3(depth(t2)), depth(t2)
c
19        end do
20      end do
c
c ********************************************************************
c * this section calculates the relative elevation of the marsh at the *
c * end of the year                                                  *
c ********************************************************************
c
        relelv(time)  = intelv+depth(time)-(slr*time)-(subsid*time)
c
c
c this loop prints at the end of all calculations - for checking
data/program
c
c       do 90 t3 = 1, time
c         write(6, 1005) totorg(t3), min(t3), h2o(t3), totvol(t3), t3
c90      end do
100   end do
c
c     do 105 time = 1, endtim
c       orgdiff(time) = totorg(time) - totorg(time-1)
c       pctdiff(time) = orgdiff(time)/totorg(time)
c105  end do
c
c to get the output to print to the screen delete the commented lines
c from the next loop   -   110
c
c     do 110 time = 1, endtim
c       write(6,1004) totorg(time),min(time),pore(time),totvol(time),
c    &   depth(time), relelv(time), time
c110  end do
c
c
c
c    this is the loop that I need to use to print the data
c    to a file for sigmaplot graphs
      write (25,*) '   totorg    min       pore      totvol    orgvol
     &   minvol    porg      bulkd   depth massabv densabv relelv  time'
      do 200 time = 1, endtim
        write (25,1001) totorg(time),min(time),
```

```
     &    pore(time),totvol(time),orgvol(time),minvol(time),porg(time),
     &    bulkd(time),depth(time),massabv(time),densabv(time),
     &    relelv(endtim-time),time
 200  end do
c
c
c     do 201 time = 1, endtim
c       write (26,1001) totorg(time),min(time),
c     &  pore(time),pctpore(time),totvol(time),minvol(time),porg(time),
c     &  bulkd(time),depth(time),massabv(time),densabv(time),
c     &  relelv(endtim-time),time
c201  end do
c
c     do 210 time =1, endtim
c       write (26,1002)
org(time,1),org(time,2),org(time,3),oldorg(time,1),
c     &  oldorg(time,2), pctpore(time), time
c210  end do
      finelv = relelv(1)
      acc1000 = depth(1000)
      acc4000 = depth(4000)
      acc4900 = depth(4900)
      do 250 time = 1, 4900
c
        if (time .le. 1000) then
          org1000 = org1000 + totorg(time)
          min1000 = min1000 + min(time)
        end if
c
        if (time .le. 4000) then
          org4000 = org4000 + totorg(time)
          min4000 = min4000 + min(time)
        end if
c
        if (time .le. 4900) then
          org4900 = org4900 + totorg(time)
          min4900 = min4900 + min(time)
        end if
c
250   end do
      write (6,1050) acc1000, org1000, min1000
      write (6,1051) acc4000, org4000, min4000
      write (6,1052) acc4900, org4900, min4900
      write (6,1053) finelv
c
c
999   format (2(f9.5, 1x))
1001  format (8(f9.5, 1x), 4(f8.2, 1x),i5)
1002  format (6(f12.8, 1x), i5)
1004  format (' org, min, pore, totvol, depth, relelv, time', f7.5,1x,
     & 2(f7.3,1x),3(f9.4,1x),i5)
1005  format ('in the loop' 4(f10.3, 2x), i5)
1010  format ('beginning of loop', f6.2, i5, f15.5, f10.3)
1015  format(' organic subsections/pre loop' 3(f6.4, 2x))
1016  format(' organic subsections/post loop' 3(f6.4, 2x))
1030  format (' rlelv, int, depth, slr, sub,time', 3f6.3, i5)
1050  format (' acc, org & min rates for 1000 years ', 3(f10.3, 2x))
```

```
1051  format (' acc, org & min rates for 4000 years', 3(f10.3, 2x))
1052  format (' acc, org & min rates for 4900 years', 3(f10.3, 2x))
1053  format (' final surface elevation            ', f10.3)
1055  format ('value of t2 at end of loop  ', i5)
2006  format ('if loop for porespace', i5)
2010  format ('porespace calcs', 4(f8.4, 2x))
      end
c
c
c
c
*************************************************************************
*
c *
*
c *                          SUBROUTINES
*
c
*************************************************************************
*
c
c
c
c *********************************************
c *  RTPROD                                    *
c *  Root production subroutine                *
c *********************************************
c  What follows is a subroutine for determining organic
c  production at various time / depths
c  1/11/94 - I am changing this so root production decreases \
c  exponentially with depth.
c  sed2.for has the old version of root production.
c
      real*8 function rtprod(t,d)
      real*8 kdist, d
      real*8 undpro
c
c parameters:
c depth(t2) is the only parameter - it is passed
c as the single variable "d"
c
c variables:
c     undpro - total underground production (g/cm^3)
c     kdist - controls the decay of the root production function
c
        if (t.le.9) then
        undpro = 0.17
        dist = 1
        else
        undpro =0.2
        dist = 1
        end if
c
c
c
c this section calculates root production at a particular depth
c based on the parameters/curve that are designated above.
```

```
c
c
      rtprod = (exp(-kdist*d)*(kdist)*undpro)
      return
      end
c
c ************************************************
c *           DECMP1                             *
c * Decomposition of "youngest" organic material  *
c ************************************************
c
c
c the next section is the decomposition subroutine FOR 1st year org matter
c it is a function that gives a decomposition rate (from 0 to 1)
c based on the depth of each section.
c
c decomp is a RATE (units g lost/g present) so it has
c to be multiplied by the organic mass (org) of each section
      real*8 function decmp1(d,kdec)
      real*8 mx1, kdec, d
c
c as with the production function the only thing that determines
c this is the depth.
c
c Variables:
c     mx1 - maximum rate of decay for this age class
c     kdec1 - k for exponential decay curve for this
c           age class decompostion curve
      mx1 = 0.92
C     kdec1 = 1.31
c
      decmp1 = (exp(-kdec*d))*mx1
      return
      end
c
c
c
c ************************************************
c *           DECMP2                             *
c * Decomposition of "medium" organic material    *
c ************************************************
c
c
c
c the next section is the decomposition subroutine FOR 2nd year org matter
c it is a function that gives a decomposition rate (from 0 to 1)
c based on the depth of each section.
c
c decomp is a RATE (units g lost/g present) so it has
c to be multiplied by the organic mass (org) of each section
c
      real*8 function decmp2(d)
      real*8 mx2, kdec2, d
c
c as with the production function the only thing that determines
c this is the depth.
c
```

```
c Variables:
c     mx2 - maximum rate of decay for this age class
c     kdec2 - k for exponential decay curve for this
c           age class decompostion curve
      mx2 = 0.37
      kdec2 = 0.57
      decmp2 = (exp(-kdec2*d))*mx2
      return
      end
c
c
c
c ************************************************
c *           DECMP3                             *
c * Decomposition of "oldest" organic material    *
c ************************************************
c
c
c
c the next section is the decomposition subroutine FOR old org matter
c it is a function that gives a decomposition rate (from 0 to 1)
c based on the depth of each section.
c
c The rates are LOWEST for this group of organic material
c
c decomp is a RATE (units g lost/g present) so it has
c to be multiplied by the organic mass (org) of each section
c
      real*8 function decmp3(d)
      real*8 mx3, kdec3, d
c
c as with the production function the only thing that determines
c this is the depth.
c
c Variables:
c     mx3 - maximum rate of decay for this age class
c     kdec3 - k for exponential decay curve for this
c           age class decompostion curve
      mx3 = 0.16
      kdec3 = 0.1
c
      decmp3 = (exp(-kdec3*d))*mx3
      return
      end
c
c
c ****************************************************
c *            PORESP                                *
c * Subroutine for determining changes in pore space  *
c ****************************************************
c
c the next section calculates the pore space for each section.
c This is where changes due to compaction occur. I am assuming that
c all of the pore spaces are filled with water, and that any compaction
c is due to the loss of water and decrease in pore space volume.
c Pore space is assumed to be a function of the amount of material
c (both organic and mineral) that is in a given section, as well
```

```
c as the mass above that particular section.
c
c a = totorg(t2)
c b = min(t2)
c c = densabv(t2)
c d = oldorg(t2)
c e = min(t2)
c
c k1 is a constant that affects the curve for compaction
c k2 affects the relative importance of organic versus mineral
c matter in determining pore space.
c K2 > 1 - organic matter more important
c k2 < 1 - organic matter less important
c k2 = 1 - organic and mineral matter the same
c
c
c p1 & p2 are just temporary variable to make calculations easier.
c
      real*8 function poresp(c)
      real*8 c,k1
      k1 = 10
      poresp = 1-(c/(k1+c))
c     k2 = 0.1
c     poresp = (1/(1+(k1*c)))
c
c everything below here has been commented out in order to
c "simplify" the calculation of pore space.
c
c     write(6,2005) a,b,c,d,e
c     if (((k2*d)+e).le.0) then
c           p2 = 1
c     else
c           p2 = sqrt(((k2*a)+b)/((k2*d)+e))
c     end if
c     poresp = p1*p2
      return
2005  format ('porespace loop', 5(f12.4, 1x))
      end
c
c
c *************************************************************
c *                       RTEMIN                              *
c * Subroutine for determining the rate of mineral sed input  *
c *************************************************************
c
c
c this section calculates the amount of mineral sediment
c input each year - based on the relative elevation of the
c marsh surface.  Y is the relative elevation of
c the core at at given time.
c tdrnge is the tidal range in meters
c mhw is the relative elevation of mhw in meters (0 in this case)
c
      real*8 function rtemin(y)
      real*8 tdrnge, mw, y
      real tdhght
      tdrnge = 999999
```

```
      mw = 0.0
      tdhght = (y-mw)/(tdrnge/2.0)
      if (tdhght .le. 0.0) then
            rtemin = 1.0
c     write (6, 2001) y, rtemin
      else
            rtemin = 1 - (min(tdhght, 1.0))
c     write (6,2002) y, rtemin
      end if
2001  format (' if part of loop, relelv, rtemin', f6.2, f6.2)
2002  format ('  else part of loop, relelv, rtemin', f6.2, f6.2)
      return
      end
```

Input files

Orgin.txt

1	0.17
2	0.17
3	0.3
4	0.14
5	0.2
6	0.25
7	0.26
8	0.26
9	0.23
10	0.22
11	0.22
12	0.22
13	0.22

porelim.txt

1	0.9
2	0.9
3	0.9
4	0.9
5	0.9
6	0.9
7	0.9
8	0.905
9	0.925
10	0.925
11	0.925
12	0.925
13	0.925

decmpin.txt

1	0.99
2	0.99
3	0.99
4	1.31
5	1.31
6	1.31
7	1.61
8	1.61
9	1.61
10	1.61
11	1.61
12	1.61
13	1.61

h2oin.txt

1	0.92
2	0.92
3	0.92
4	0.93
5	0.93
6	0.905
7	0.905
8	0.96
9	0.96

```
10    0.976
11    0.976
12    0.976
13    0.976
```

minin.txt

```
1     0.08
2     0.08
3     0.05
4     0.02
5     0.02
6     0.01
7     0.01
8     0.007
9     0.007
10    0.007
11    0.007
12    0.007
13    0.007
```

Output file sksxx.dat

totorg	min	pore	totvol	orgvol	minvol	porg	bulkd	relelev	time
0.21712	0.007	2.22104	2.41418	0.19045	0.00268	0.96877	0.09283	19.7	1
0.21656	0.007	6.56681	6.75946	0.18997	0.00268	0.96869	0.03307	16.6	2
0.21128	0.007	5.58239	5.77041	0.18534	0.00268	0.96793	0.03783	13.43	3
0.20757	0.007	4.90441	5.08917	0.18208	0.00268	0.96738	0.04216	0.9	4
0.21547	0.007	4.63679	4.82848	0.18901	0.00268	0.96854	0.04607	-4.85	5
0.24402	0.007	4.84753	5.06427	0.21405	0.00268	0.97211	0.04957	-16.71	6
0.24112	0.01	4.50417	4.71951	0.21151	0.00383	0.96018	0.05321	-18.75	7
0.22322	0.01	3.94111	4.14075	0.19581	0.00383	0.95712	0.05632	-18.91	8
0.16717	0.02	2.89629	3.05059	0.14664	0.00766	0.89314	0.06135	-20.66	9
0.1043	0.02	1.78043	1.87958	0.09149	0.00766	0.8391	0.06613	-22.62	10
0.23962	0.05	3.96078	4.19013	0.21019	0.01916	0.82736	0.06912	-25.88	11
0.12486	0.08	2.3388	2.47898	0.10953	0.03065	0.6095	0.08264	-27.89	12
0.12044	0.08	2.204	2.3403	0.10565	0.03065	0.60088	0.08565	-30	13

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