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RESEARCH

Simulation of Subsidence Mitigation Effects on Island Drain Flow, Seepage, and Organic Carbon Loads on Subsided Islands, Sacramento–San Joaquin Delta

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ABSTRACT

In light of desired implementation of subsidence mitigation practices on Delta islands and the need for evaluation tools, we developed groundwater-flow and solute-transport models and attempted to answer the following questions.

1. How do the groundwater-flow and drainage systems interact to influence island drainage volumes and drain dissolved organic carbon (DOC) concentrations and loads?
2. How will future subsidence affect drainage volumes, DOC loads, and seepage onto islands?
3. How will land-use changes to mitigate subsidence affect seepage, drain flow, and DOC loads?
4. How can seepage and water-quality effects from drainage, restoration, and rice cultivation on Delta islands be minimized?

We used hydrologic and geochemical data and modeling to answer these questions. Subsurface processes dominate subsided Delta island hydrology. Seepage and siphoned irrigation water recharge groundwater, which flows to drains. Drainage water that contains DOC derived from oxidation of organic soils is discharged to adjacent channels. We analyzed the effects of subsidence mitigation by simulating mosaics of rice and palustrine wetlands with varying hydrologic management on a representative subsided island (Twitchell Island). These alternative land uses reduce seepage onto islands and thus contribute to increased levee stability. However, most scenarios resulted in increased drain flow and DOC loads. Reducing drain flow is essential to reducing DOC loads relative to the business-as-usual scenario and can be accomplished through hydrologic controls that reduce drain flow on the islands.

KEY WORDS

Subsidence, sustainability, groundwater, water quality

INTRODUCTION

Subsidence in the Sacramento–San Joaquin Delta (Delta) (Deverel and Rojstaczer 1996) began in the late 1800s as lands were cleared and dewatered for agriculture. Since then, island elevations have decreased to as much as −9 m MSL and are imperfectly protected from flooding by over 1,800 km of man-made levees. Subsidence contributes to levee instability and water supply vulnerability (e.g., Mount and Twiss 2005; Prokopovitch 1985; Deverel et al. 2016b). Networks of ditches collect and transport shallow groundwater to pumps that discharge to adjacent channels.

Twitchell Island hydrology is typical of subsided Delta islands; water flows from sloughs and river channels through and underneath levees into groundwater. Stable isotopes in water demonstrated the connectedness of channel water and groundwater throughout the Delta (Deverel et al. 2007a; HydroFocus 2015). Moreover, a portion of the water siphoned onto islands for irrigation infiltrates to become shallow groundwater that flows to island drainage ditches.

California recognizes the need for subsidence mitigation. Rice cultivation and permanently flooded palustrine wetlands (Whipple et al. 2012) mitigate subsidence (Deverel et al. 2016a; Miller et al. 2008). Tools are needed that can lead to outcomes for subsidence-mitigation projects that will meet Delta Science Plan management objectives (DSC 2016) and not result in deleterious collateral water-quality effects. Dissolved organic carbon and associated disinfection byproducts are key water-quality issues. Heretofore, tools to evaluate alternative land uses on subsided islands were lacking. Implementation of alternative subsidence-mitigating land-use strategies requires quantitative understanding of the effects of these strategies on drainage volume, DOC loads, and trihalomethane formation potential (THMFP), and ways in which water-quality effects can be minimized. To develop improved understanding, we attempted to answer four questions as follows.

1. How do the groundwater-flow and drainage systems interact to influence island drainage volumes, drain DOC concentrations, and loads?
2. How will future subsidence affect drainage volumes, DOC loads, and seepage onto islands?
3. How will land-use changes to mitigate subsidence affect seepage, drain flow, and DOC loads?
4. How can seepage and water-quality effects from drainage, restoration, and rice cultivation on Delta islands be minimized?

To answer these questions, we (1) used pre-existing data and modeling, (2) collected additional chemical and physical data on Twitchell Island, and (3) developed and refined groundwater-flow and solute-transport models. Our results can be applied to subsided Delta islands that have organic soils.

BACKGROUND

Soils

Delta organic deposits formed during the last 7,000 years under tidal wetland conditions (Atwater et al. 1977; Atwater 1980, 1982). Plant material accumulated under anaerobic conditions as sea level rose (Shlemon and Begg 1975; Drexler et al. 2009). Thicknesses of remaining organic deposits generally increase from east to west (Deverel et al. 2015); ranging from less than 1 m on the eastern, southern, and northern margins of the Delta to over 10 m in the western Delta.

Processes Affecting Water Quality

The Delta provides a portion of the drinking water for nearly two-thirds of the state's population. Concentrations of DOC in Delta export waters can be problematically high because of the formation of disinfection byproducts (DBPs) such as trihalomethanes (THMs) and result in relatively high costs for municipal water treatment (Chen et al. 2010). Agricultural drainage from Delta island organic soils contributes substantially to the THMFP at Delta export pumps (Amy et al. 1990; Kraus et al. 2008).

The highest DOC and THMFP concentrations at drinking water intakes (e.g., Harvey O. Banks pumping plant) occur during the winter and early spring (Figure 1). Although various physical and chemical variables influence DOC formation and release (Christ and David 1996; Moore 1998; Kalbitz et al. 2000; Moore and Dalva 2001; Aguilar and Thibodeaux 2005), hydrologic processes are consistently the dominant control on DOC export in natural systems (Urban et al. 1989; Hogg et al. 1992; Hope et al. 1994; Kalbitz et al. 2000). On Twitchell Island, higher pore-water DOC concentrations were associated with higher organic-matter surface soils (Fleck et al. 2004). On three Delta islands (Jersey

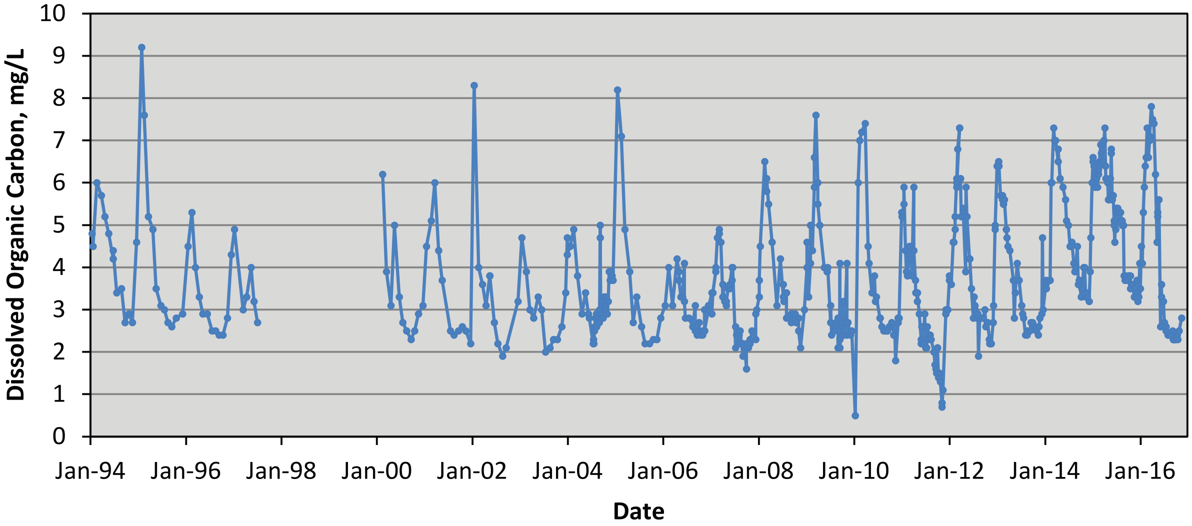

Figure 1 DOC concentrations at the Harvey O. Banks Pumping Plant

Island, Sherman Island, and Orwood Tract), the highest DOC drainage concentrations and loads were associated with high groundwater levels (Deverel and Rojstaczer 1996).

Oxidation of soil organic matter and subsequent mobilization determine the spatial and temporal variability of island DOC and DBP drain loads and concentrations (Deverel et al. 2007a). Soil organic matter oxidation in shallow soils results in high pore-water DOC concentrations, which during the late fall and winter are mobilized and cause large drainage DOC and THMFP loads. Deverel et al. (2007a) also demonstrated that soil organic matter oxidation contributes salinity to soil water that is transported to drainage ditches. As the organic soils are oxidized and release CO_2, inorganic constituents present in the peat (e.g., sulfate, calcium, and magnesium) remain to dissolve in percolating water.

Water movement in peat soils is a controlling ecological factor (Hammond et al. 1990; Ingram 1991) and therefore “practitioners of peatland hydrology will benefit by employing reliable subsurface simulation models to provide input to management decisions” (MacAlister and Parkin 1998). Multiple studies illustrate the complexity of groundwater flow and solute transport in organic soils. Holden and Burt (2003) and other authors (e.g., Ingram 1982; Kirkby et al. 1995; Hilbert et al. 2000) assessed the traditional layered peat paradigm; an aerated, near-surface, acrotelm underlain by an anaerobic catotelm. The shallow acrotelm, which is characterized by a fluctuating water table, is highly hydraulically conductive and rich in microorganisms and vegetation. The catotelm water content is generally temporally constant, and hydraulic conductivity is relatively low. This conceptual model generally fits Delta organic soils where decomposed, variably saturated, and relatively highly hydraulically-conductive peat overlies minimally decomposed, saturated, and less hydraulically-conductive peat. Deverel (1983) and Deverel et al. (1986) documented the oxidation-reduction potential as ranging from generally oxidizing or slightly reducing in the acrotelm to strongly reducing in catotelm as well as the occurrence of sulfate and iron reduction. Methanogenesis occurs deep in the acrotelm and in the catotelm, but CH_4 is oxidized to CO_2 in the unsaturated acrotelm (Oremland and Culbertson 1992; Knox et al. 2015).

Peat Water- and Solute-Transmitting Properties

Water-transmitting properties of organic soils vary with depositional nature, microbial activity, hydraulic gradients, gas accumulation, and compressive load (Ingram et al. 1974; Rycroft et al. 1975a, 1975b; Dasberg and Newman 1977; Hemond and Goldman 1985; Mathur and Levesque 1986; Chason and Seigel 1988; Reynolds et al. 1992; Baird and Waldron 2003). Hydraulic conductivity has also been related to the degree of decomposition (Rycroft et al. 1975b; Eggelsmann et al. 1993).

Burow et al. (2005) reported hydraulic conductivity values ranging from 0.003 to 30 $\mathrm{m\,d^{-1}}$ for organic soils worldwide. Desiccation cracks and stress fracturing influence groundwater flow and solute transport in Delta organic soils (Hanson and Carlton 1985). Ours et al. (1997) suggested a dual-porosity model for organic soils; macro porosity transmits water rapidly relative to micro porosity and less mobile pore water. McBrierty et al. (1996) described four forms of water in peat: absorbed or tightly bound water; two forms of loosely bound water; and bulk water.

Groundwater-Flow and Solute-Transport Simulation in Peats

Several researchers successfully simulated groundwater flow and solute transport in organic deposits, and provided important information. Reeve et al. (2001) used MODFLOW (McDonald and Harbaugh 1988) to simulate the interaction of regional and localized groundwater flow, and demonstrated the importance of mechanical dispersion for solute transport. McKenzie et al. (2002) simulated groundwater flow and solute transport in a Swiss peat bog. Hoag and Price (1997) conducted laboratory column experiments which suggested the importance of considering the dual-porosity matrix for solute movement. Burow et al. (2005) developed two-dimensional groundwater-flow and heat-transport models using SUTRA (Voss 1984) on Twitchell Island to simulate DOC drainage loads. Harvey et al. (2005) successfully simulated a tracer experiment in Florida peat soils.

APPROACH

Prompted by high winter and spring Delta-channel DOC concentrations (Figure 1), Deverel et al. (2007b) developed a steady-state groundwater-flow model that represented winter 2003 conditions (Winter 2003 model), which indicated increased seepage, DOC loads, and drain flow with continuing subsidence. Simulation of subsidence mitigation reduced winter seepage, drain flow, and drain DOC loads relative to the status quo. We developed a Winter 2013 steady-state model and a transient model for this study to better simulate potential subsidence-mitigating land use changes.

Site Description and Methods

Remnants of the Delta Holocene depositional history on Twitchell Island (Deverel et al. 2007a) revealed 3 to 5 m of organic deposits, accumulated during the last 7,000 years (Atwater 1980; Drexler et al. 2009), overlying mineral deposits. A thin chemically reduced blue (because of the presence of ferrous iron) clay denoted as tidal mud by Atwater (1980) immediately underlies the organic deposits. Coarser materials of primarily Sierran origin underlie the tidal mud. Tugel (1993) described Twitchell Island soils as Rindge mucky silt loam (Euic, thermic Typic Medisaprists) formed from tules and reeds with minor amounts of alluvium. The USDA currently classifies this soil as a Euic, thermic Typic Haplosaprists[1]. Reported organic carbon content of Twitchell Island surface soils ranged from 18% to 28% (Fujii et al. 1998; Fleck et al. 2004).

Data-collection efforts occurred on three areas of Twitchell Island (Figure 2), as described in Deverel et al. (2007a, 2007b) and Deverel et al. (2016a). During 2000–2003 and 2009–2013, drain flow, groundwater level, and aquifer-parameter data were collected. Water samples from wells and drainage ditches were analyzed for inorganic and organic constituents. Deverel et al. (2007a) developed a conceptual model for processes that resulted in temporal and spatial variability in DOC and THMFP drain loads. These data and concepts were used in the development of groundwater-flow and solute-transport models.

Hydrologic Data Collection

In 2001 and 2003, 22 monitoring well clusters of one to four wells were installed on Twitchell Island (Deverel et al. 2007b). In 2009 and 2012, 68 additional monitoring wells were installed at 25 well cluster sites (Figure 2). Well depths ranged from 0.3 to 10 meters below land surface. Water levels were measured in all wells approximately monthly, including monitoring wells installed in the CDWR experimental subsidence-reversal wetlands (Figure 2)

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[1] *https://soilseries.sc.egov.usda.gov/OSD_Docs/R/RINDGE.html*

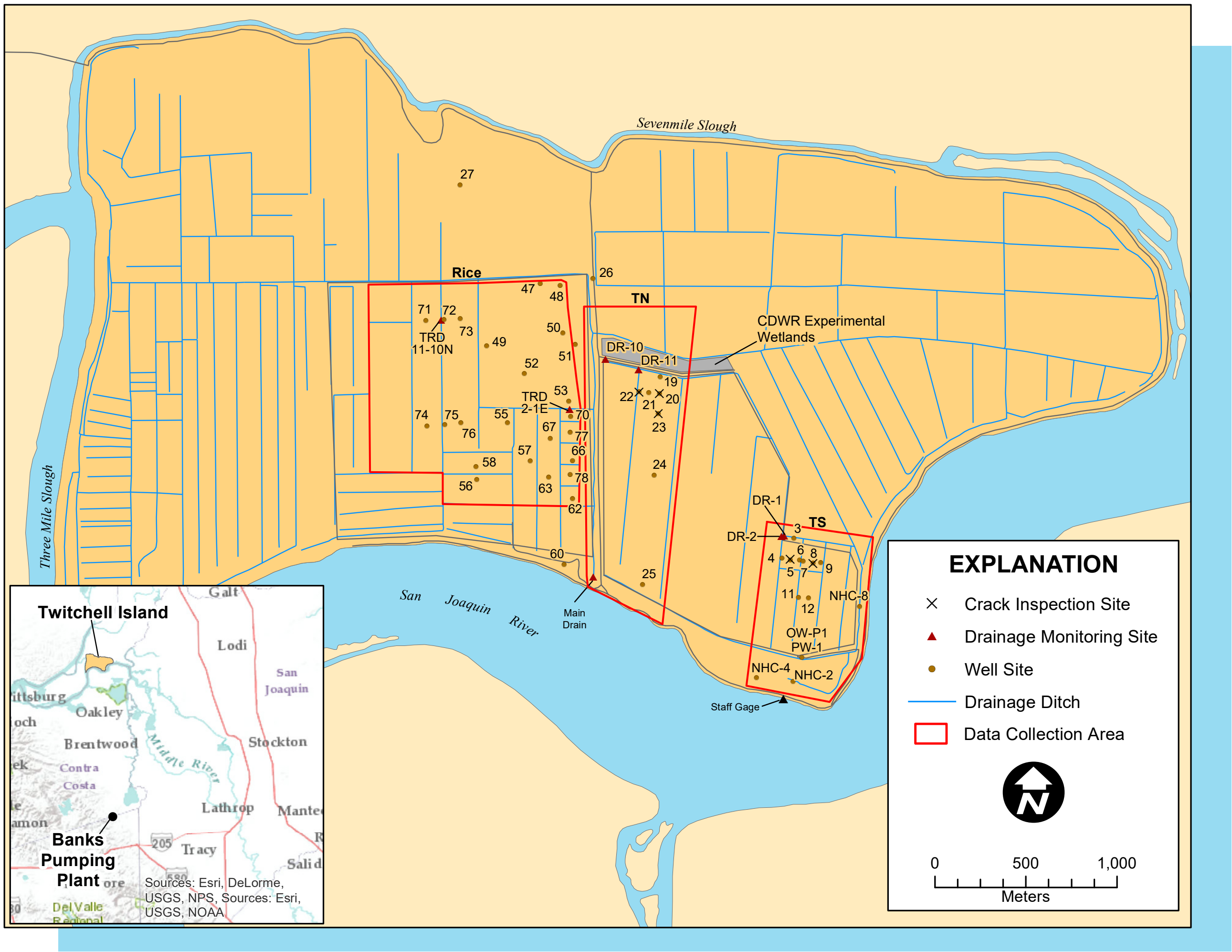

Figure 2 Location of Twitchell Island, monitoring well locations, areas where data were collected, and CDWR wetlands

(Gamble et al. 2003). Transducers and data recorders were used in selected wells and the San Joaquin River. From 2001 to 2003, drain flow was measured approximately biweekly to monthly at four weir locations (DR1, DR2, DR10, and DR11; Figure 2) (Deverel et al. 2007a, 2007b). In 2012 and 2013, hourly drain flow was measured at two drainage ditch locations adjacent to rice fields. Drain flow was measured continuously using McCrometer propeller flow meters at the main discharge point for the entire island (labeled as “Main Drain” on Figure 2).

Chemical Data Collection

Drain-water samples were collected, and electrical conductivity (EC), pH, temperature, and dissolved oxygen (DO) were measured at weirs and the island main drainage discharge outlet. Groundwater samples were collected and EC, pH, temperature, oxidation-reduction potential (E_h), and DO were measured in all wells. Constituents analyzed were described in Deverel et al. (2007a); and Kirk et al. (2015).

Hydraulic Conductivity Measurements and Calculations

We estimated hydraulic conductivity using single-well response (slug) tests and tidal analysis in 92 wells. We also estimated groundwater hydraulic conductivity of the lower, confined mineral aquifer using groundwater age dating (tritium and helium analysis of groundwater samples) as described in Deverel et al. (2007b). Details of the methods used to estimate hydraulic conductivity are provided in Appendix A.

Numerical Groundwater-Flow and Solute-Transport Model Development

We developed steady-state and transient groundwater-flow models using the USGS MODFLOW-2000 code. The winter 2003 (Deverel et al. 2007b) model was updated and simulates average conditions for the period December 2012 through March 2013 (Winter 2013 model). The California Department of Water Resources (CDWR) classified water year 2013 as dry.[2] The transient model simulates weekly conditions during December 2012 through November 2013. Appendix B provides a detailed description of the groundwater-flow models and sensitivity analysis.

We developed a steady-state winter model because data described previously show that the largest in-channel DOC concentrations and on-island drainage DOC loads occur during this time. We used the model to simulate alternative land-use scenarios to compare with the baseline (business-as-usual; BAU) model results. Because the alternative scenarios involve land inundation with water from adjacent channels, and the average water levels in the adjacent channels were not substantially different relative to average hydrologic conditions, we opine that low winter precipitation during this dry year does not affect our ability to assess changes in seepage, drain flow, and loads associated with alternative land uses.

We used a solute-transport model (MT3DMS) coupled with the groundwater-flow models to simulate subsurface DOC movement to drainage ditches, and to evaluate the effects of varying management practices on island drainage DOC loads. Appendix C provides a detailed description of the solute-transport model.

Simulation of Effects of Land- and Water-Management Practices

We employed the winter 2013 steady-state model to evaluate the effects of subsidence-mitigation practices by simulating (1) present-day practices, which included subsidence and sea level rise, and (2) seven alternative land-use scenarios. We simulated each land-use scenario using 2007 and estimated 2050 land surface elevations (Table 1). We repeated some of the scenarios with the transient model (Table 1). Scenarios represent mosaics of rice and wetlands (Figure 3), which we compared with the BAU case in which corn, alfalfa, and pasture were the primary land uses. For the scenarios representing future subsidence to 2050, we decreased land surface elevation using methods described in Deverel and Leighton (2010) and Deverel et al. (2016a). We also increased the specified head representing channel water elevation around the island by 7 cm to simulate sea level rise to 2050.

Deverel et al. (2007b) presented evidence that maintaining drainage-ditch water levels near land surface will reduce drain-water DOC loads. For scenarios with drain-water-level elevations at land surface, we set the drain stage equal to model cell top elevations. For steady-state model scenarios with rice and wetlands, constant-head cells were specified to simulate standing water.

RESULTS

Groundwater Conditions

Upward vertical groundwater hydraulic gradients were prevalent, and water levels in wells screened in the underlying mineral aquifer were consistently close to or above land surface. Water levels in wells screened in the organic deposits were near or above land surface during the winter, and decreased to over 1 m below land surface during summer. Groundwater flows from the San Joaquin River and Sevenmile Slough toward the center of the island, and discharges to drainage ditches (Figure 4). Surface water flowing adjacent to Twitchell Island contains about 4 mg L^{-1} DOC (Deverel et al. 2007a). Deverel et al. (2015) illustrated flow from Delta channels through and under levees onto subsided islands.

For all water level measurements from 2003 to 2013, horizontal hydraulic gradients in the organic and mineral deposits from Well NHC-4 to Well site 19 (see Figure 2 for well locations) ranged from 0.0013 to 0.0025. Larger values occurred during the late summer and early fall in the organic deposits, but there was little seasonal variation in the mineral

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[2] *http://cdec.water.ca.gov/cgi-progs/iodir/wsihist*

Table 1 Simulated modeling scenarios representing land- and water-management scenarios

Scenario	Land use	Elevation	Figure number	Transient model simulations
1	Rice cultivation on 194 ha (2013)	2007	3a	
1a	Rice cultivation on 194 ha (2050)	2050	3a	
2	Rice and wetlands on 522 ha (2013)	2007	3b	yes
2a	Rice and Wetlands on 522 ha (2050)	2050	3b	
3	Wetlands (-3m and below), Rice at periphery. (2013)	2007	3c	yes
3a	Wetlands (-3m and below), Rice at periphery. (2050)	2050	3c	
4	Rice (-3m and below), Wetlands in the periphery (2013)	2007	3d	yes
4a	Rice (-3m and below), Wetlands in the periphery (2050)	2050	3d	
5	Rice (-3m and below), Wetlands in the periphery, water levels in drainage ditches at land surface (2013)	2007	3d	yes
5a	Rice (-3m and below), Wetlands in the periphery, water levels in drainage ditches at land surface (2050)	2050	3d	
6	Wetlands (-3m and below), Rice at periphery, water levels in drainage ditches at land surface.(2013)	2007	3c	yes
6a	Wetlands (-3m and below), Rice at periphery, water levels in drainage ditches at land surface (2050)	2050	3c	
7	Wetlands on entire island, water levels in drainage ditches at land surface (2013)	2007	3e	yes
7a	Wetlands on entire island, drain elevations at land surface (2050)	2050	3e	
8	Twitchell Island with drains (Removing Rice from Run 1) (2013)	2007	3f	yes
8a	Twitchell Island with drains (Removing Rice from Run 1a) (2050)	2050	3f	

aquifer. The median upward vertical gradient in the organic deposits was 0.15, and values ranged from 0.02 to 0.52. The median upward vertical gradient from the underlying mineral aquifer to the organic deposits was 0.15, and values ranged from 0.06 to 0.32.

Island Drain Flow and Loads

Island drain flow at the main drain (Figure 2) from March 2009 to August 2014 varied seasonally from less than 37,000 $m^3 d^{-1}$ during April through October to as high as 111,000 $m^3 d^{-1}$ during November through March (Figure 5). Elevated drain total dissolved solids (TDS) and DOC loads occurred during precipitation and high drain flows, and ranged from less than 10,000 to over 40,000 $kg\,d^{-1}$ for TDS, and from less than 400 to over 1,600 $kg\,d^{-1}$ for DOC (Figure 6). Dissolved organic carbon and TDS concentrations were generally elevated during winter, and lower during the spring, summer, and fall (Figure 7). Flow in drainage ditches near the rice fields (DR 2-1E and 11-10N on Figure 2) ranged from less than 0.028 $m^3 s^{-1}$ during summer to greater than 0.11 $m^3 s^{-1}$ during winter.

Groundwater-Flow Model Inputs

Hydraulic Conductivity

Horizontal hydraulic conductivity in the shallowest wells screened between 0.3 and 0.5 m ranged from 0.01 to 36 $m\,d^{-1}$. For undisturbed horizontal cores collected within 0.6 meters of land surface by the USGS (2003 written communication from Tim Mathany, USGS, to S. Deverel, unreferenced, see “Notes”) horizontal hydraulic conductivity values ranged from 1.9 to 40.8 $m\,d^{-1}$. For the 1.2-m cores, horizontal and vertical hydraulic conductivities were 0.015 and 0.005 $m\,d^{-1}$, respectively. For the 2-m wells (model Layer 2), horizontal hydraulic conductivities ranged from 0.003 to 1.10 $m\,d^{-1}$. For the 3-m wells (model Layer 3), hydraulic conductivities ranged from 0.003 to 0.92 $m\,d^{-1}$.

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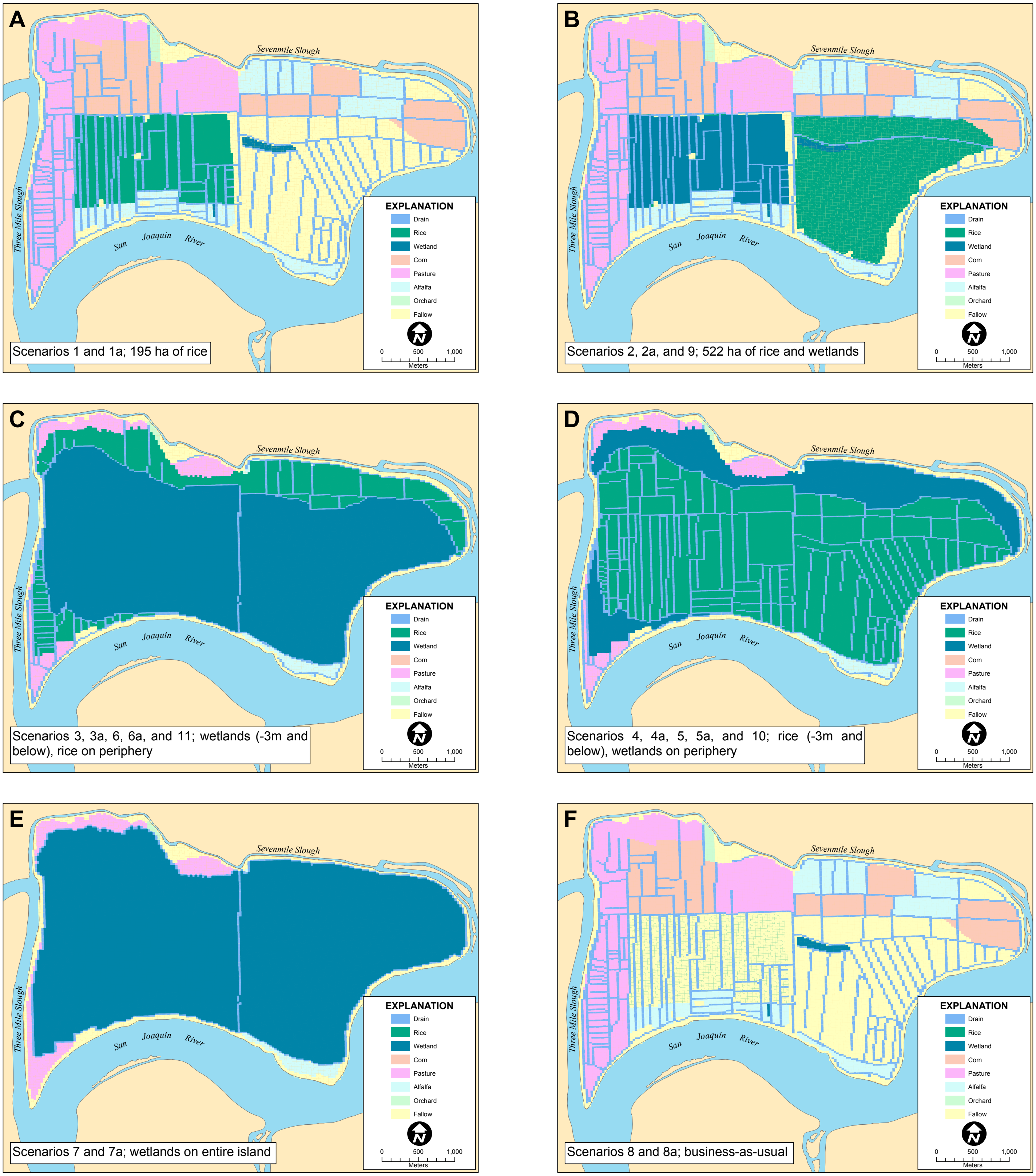

Figure 3 Land use scenarios simulated with the model

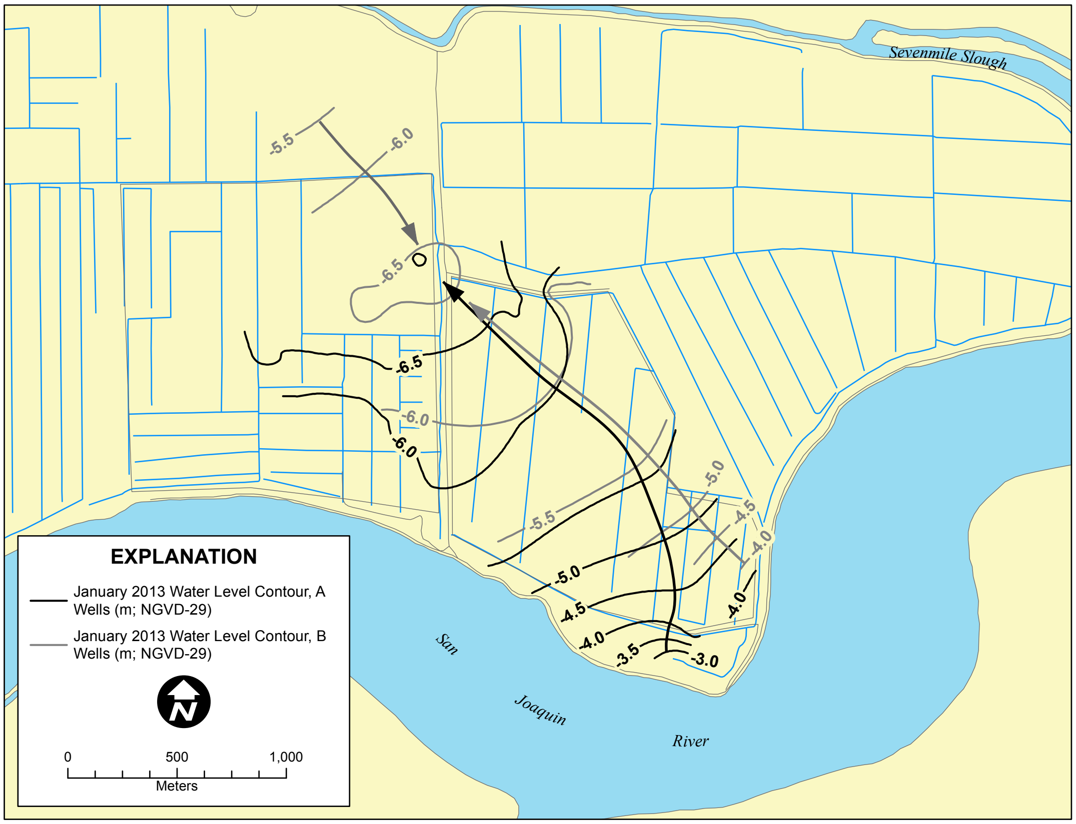

Figure 4 Contours of January 2013 water level elevation in the A and B wells.

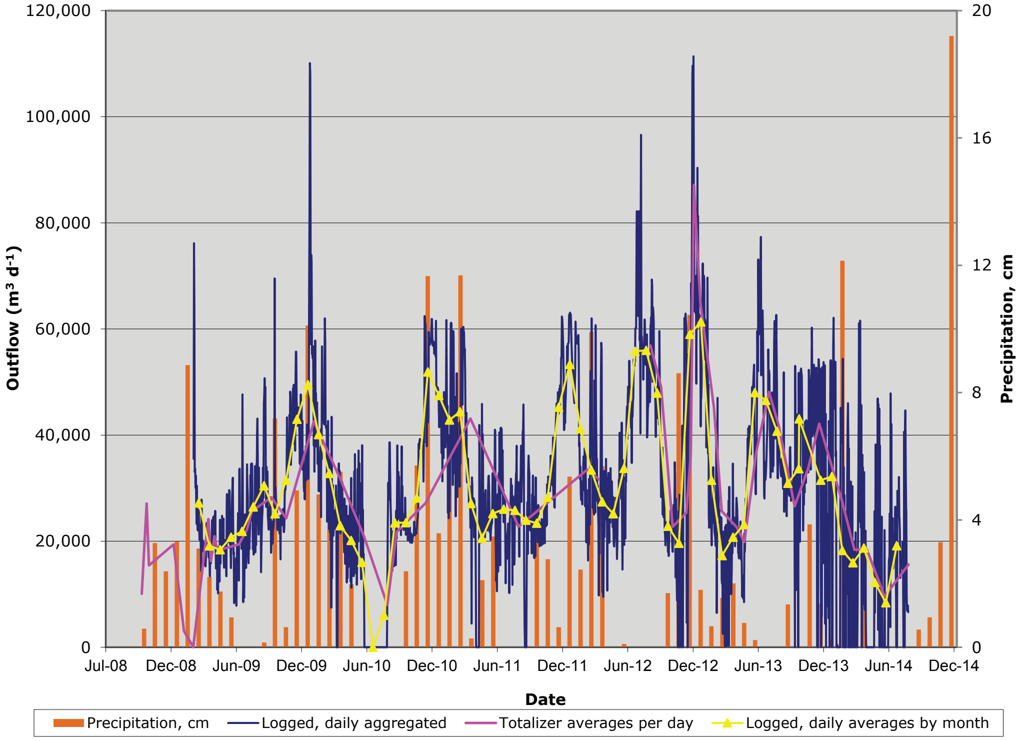

Figure 5 Island drain flow and precipitation

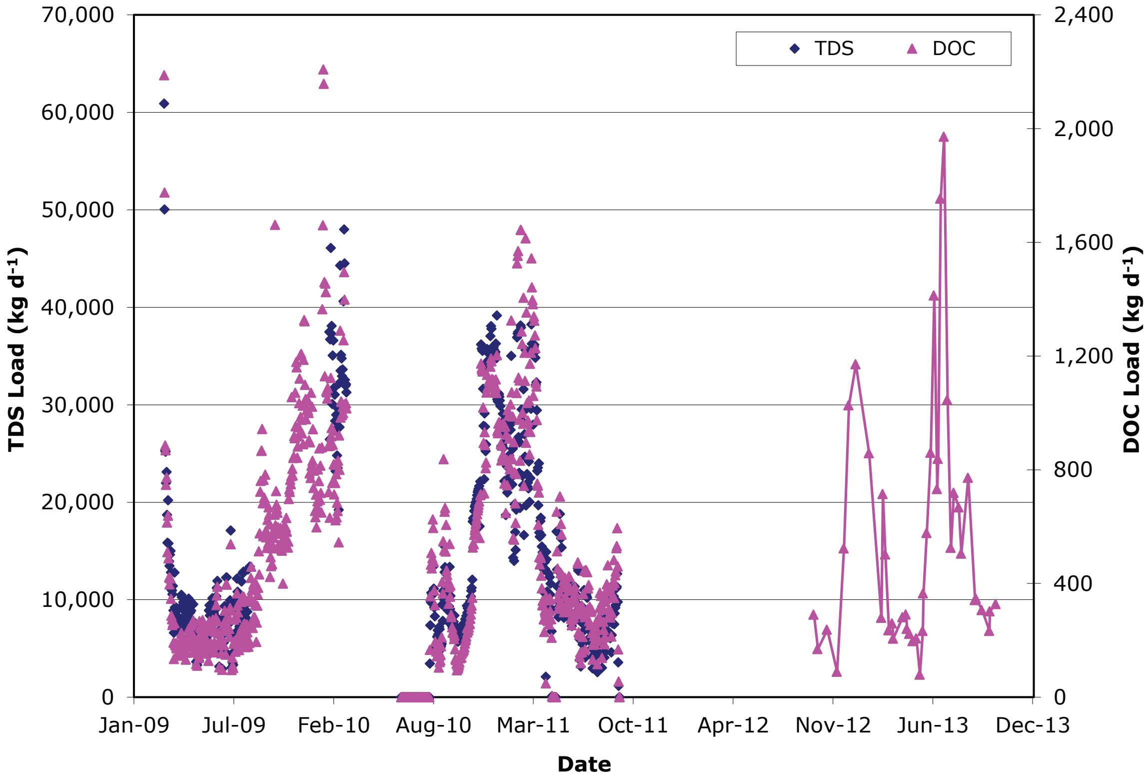

Figure 6 Island drain flow DOC and TDS loads

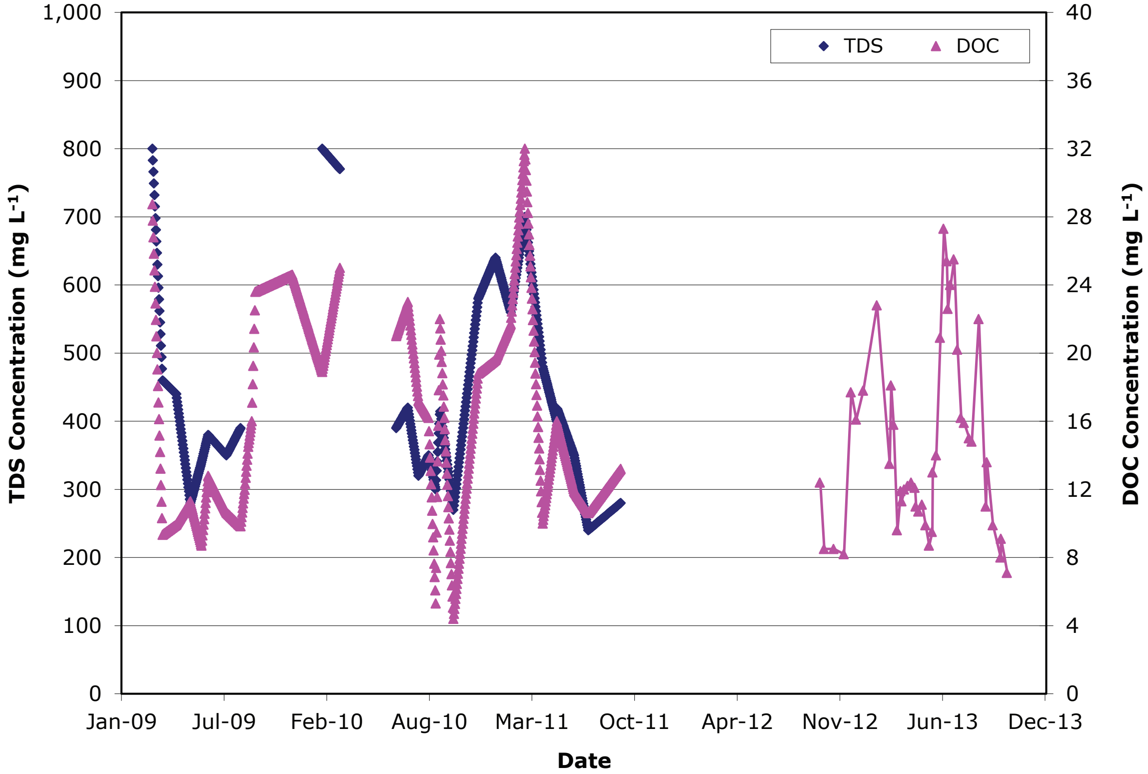

Figure 7 Island drain flow DOC and TDS concentrations

For the 28 slug tests conducted in 14 wells screened in the mineral aquifer, the geometric mean of the horizontal hydraulic conductivity was 0.17 m d^{-1} (the range was 0.015 to 1.6 m d^{-1}). Age dating results from two wells in the underlying mineral aquifer suggests that slug test results under-estimate groundwater travel times in this aquifer. Groundwater ages of samples from wells about 550 and 1,100 m from the midpoint of the San Joaquin River were 16.6 and 36.5 years, respectively. The San Joaquin River is the only recharge source for these wells in this confined aquifer. These recharge ages indicate that groundwater travelled about 30.2 to 33 m yr^{-1} from the midpoint of the San Joaquin River. Using the average horizontal gradient of 0.0017 and a porosity of 0.20, the age-dating results indicate similar horizontal hydraulic conductivity values for the two wells of 9.7 and 9.1 m d^{-1}. Considering the possible range in distance between the river (midpoint or north bank) and the wells, the hydraulic conductivity value could be as low as 6.5 m d^{-1}.

We used the tidal analysis described in Appendix A to estimate horizontal hydraulic conductivity values in wells on the perimeter of the island. For the levee materials and organic sediments between the San Joaquin River and Well NHC-2A screened within about 6 m of land surface, we estimated a hydraulic conductivity value of 0.023 m d^{-1}. We estimated a range of values by considering uncertainty in the lag time and the distance from the river to NHC-2A, which resulted in a range of 0.016 m d^{-1} to 0.031 m d^{-1}. We estimated the hydraulic conductivity between the river and Well OW-60A (labeled 60 on Figure 2) at 1.1 m d^{-1}. We conducted tidal analyses for a well screened in the mineral aquifer below the clay and a well screened in the organic materials

Table 2 Comparison of measured and modeled hydraulic conductivity values

Model Zone and Layer	Model value (m d^{-1})	Ratio of horizontal to vertical hydraulic conductivity used in model	Geometric mean and/or range of measured values (where applicable) (m d^{-1})	Method
Layer 1, well decomposed peat, high organic matter (Rindge and Gazwell)	17–20	1:1	0.52 (0.01–36) 3.7 (1.9–21.5)	Slug tests, USGS core experiments
Layer 1, clay loam (Scribner)	3.0	1:1		Calibration
Layer 2, low organic matter content, less decomposed organic deposits (Gazwell)	4.6	2:1	0.05 (0.003–1.1)	Slug tests
Layer 2, high organic matter content, less decomposed organic deposits (Rindge)	1.2	2:1	0.05 (0.003–1.1)	Slug tests
Layer 2, high organic matter content, undecomposed organic deposits, southeastern part of island (Rindge)	0.06	10:1	0.05 (0.003–1.1)	Slug tests
Layer 2, clay loam (Scribner)	3.0	1:1		Calibration
Layer 3, undecomposed organic deposits (Rindge and Gazwell)	0.27	1:1	0.07 (0.003–0.92)	Slug tests
Layer 3, undecomposed organic deposits, southeastern part of island (Rindge)	0.03	10:1	0.07 (0.003–0.92)	Slug tests
Layer 3, clay loam (Scribner)	3.0	1:1		Calibration
Layer 4, clay zone	0.00013	1:1	.000091 +/- 6.1e–6	Tidal analysis
Layer 4, clay loam zone	0.15	1:1		Calibration
Layer 5, sand	9.1-15.2	1:1	6.5–9.7	Age dating
Layers 1–4, levee material	0.024	1:1	0.023 (0.017–0.031)	Tidal analysis
Layer 5, levee material, north portion of island	0.6	1:1	0.17 (0.015–1.6) 0.53 (0.13–1.7)	Slug tests, Tidal analysis
Layer 5, levee material, east, west, and south portion of island	1.2	1:1	0.17 (0.015–1.6) 0.53 (0.13–1.7)	Slug tests, Tidal analysis

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above the clay at the same location. We assumed for this analysis that the lag time between the tidal signal in the mineral aquifer and the well screened in the organic material was a function of the clay vertical hydraulic conductivity, which we estimated at $9.1 \times 10^{-5}\,\mathrm{m\,d^{-1}}$ ($\pm 6.1 \times 10^{-5}\,\mathrm{m\,d^{-1}}$). Tidal analysis of five wells screened in the mineral aquifer near the levee resulted in hydraulic conductivities ranging from 0.13 to $1.7\,\mathrm{m\,d^{-1}}$.

Table 2 summarizes measured and modeled hydraulic conductivity values. Hydraulic conductivity values used in the Winter 2003 model were revised for the Winter 2013 model based on new information and through calibration. We determined vertical hydraulic conductivity values through model calibration. Figure 8 shows the modeled distribution of hydraulic conductivities in Layers 1 and 2 based on the 0.2-m, 0.3-m, and 2-m wells and the soils distribution from Tugel (1993). The blue area represents the levee materials; the pink area represents the highly organic matter soils in the southeastern part of the island; the dark tan area represents the higher organic matter Rindge soils in the center of the island; the green area represents the lower organic matter Gazwell soils and the rice fields; and the light tan area represents the lower organic matter/mineral soils. For model Layers 1 and 2, calibrated hydraulic conductivity values exceed or are at the upper range of measured values. Data and field observations indicated that soil cracks affect horizontal movement of water to drainage ditches.

Subsurface cracks affect lateral groundwater-flow to Delta-island drainage ditches through shallow soils within 1 m of land surface (Hansen and Carlton 1985). Penetrometer data (Deverel et al. 2007b) indicated varying spatial frequency of cracks for five grids; 2% to 32% of the penetrometer readings were zero, indicating the presence of cracks, many of which were verified by subsequent excavation. We observed less frequent subsurface cracks deeper than 0.6 m. At drainage ditches that range in depth from 1.5 to 2.5 m, we observed reddish brown water, resulting from oxidation of ferrous iron, flowing from cracks. Consistently, Burow et al. (2005) used higher-than-measured hydraulic conductivity values in simulating flow and heat transport on Twitchell Island.

Drain Conductance

Drain conductances were estimated from head difference–drain flow relations (Deverel et al. 2007b) and assigned in the model based on width and depth; values ranged from 213 to $966\,\mathrm{m^2\,d^{-1}}$.

Groundwater-Flow Model Results

We evaluated model performance using methods identified by Anderson and Woessner (2002):

- Root-mean-square-error (RMSE) of measured and simulated water levels;
- Relative error (RMSE divided by the range of measured water levels);
- Mean absolute error;
- Scatter plots of measured and simulated water levels and coefficient of determination (R^2);
- Time series plots (hydrographs) of measured and simulated water levels; and
- Scatter plots of residuals (measured–simulated water levels) versus simulated water levels.

For the winter 2013 model, the RMSE was 0.46 m, the relative error was 11%, and the mean absolute error was 0.37 m. For the transient model, the RMSE was 0.52 m, the relative error was 11%, and the mean absolute error was 0.41 m.

Figure B4 and B5 in Appendix B show the relation of measured and simulated groundwater levels for the steady-state model and the transient model. The coefficient of determination (R^2) is 0.75 and 0.70 for the steady-state and transient models, respectively. Hydrographs presented in Appendix B (Figure B6) generally show a good match between simulated and measured water levels. Scatter plots of residuals versus simulated water levels are clustered around zero, and there is no trend for the entire range of simulated water levels, thus indicating the absence of model bias.

We also assessed model performance by comparing measured and simulated drain flows; for the Winter 2013 model, measured and simulated drain flows were $42{,}600\,\mathrm{m^3\,d^{-1}}$ and $45{,}700\,\mathrm{m^3\,d^{-1}}$, respectively (7.2% difference). For the transient model, average measured and simulated drain flows

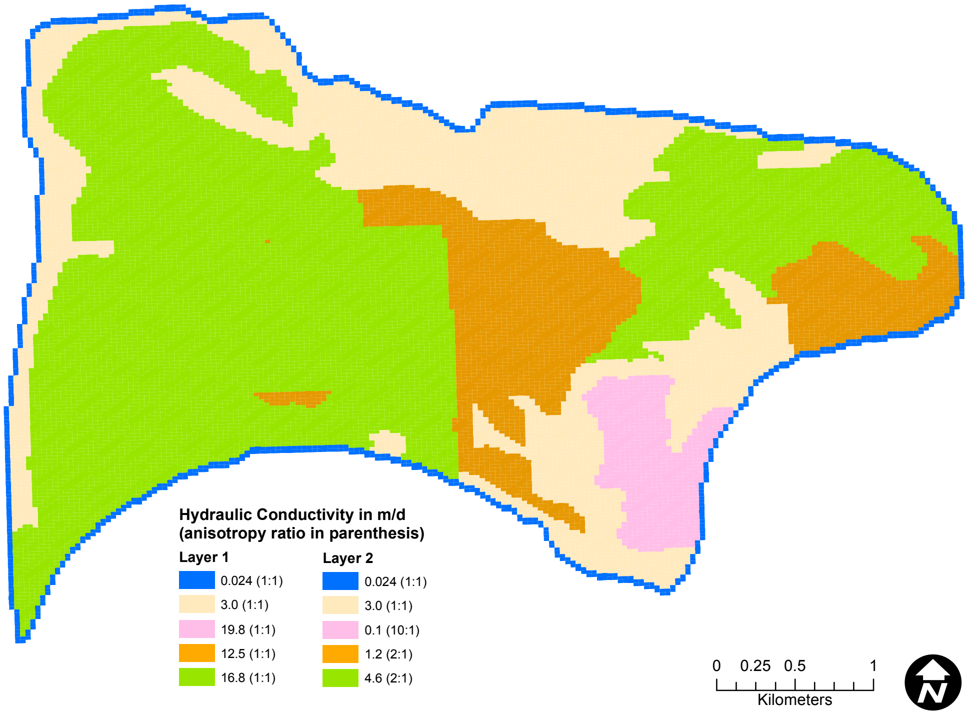

Figure 8 Modeled distribution of hydraulic conductivity for model layers 1 and 2

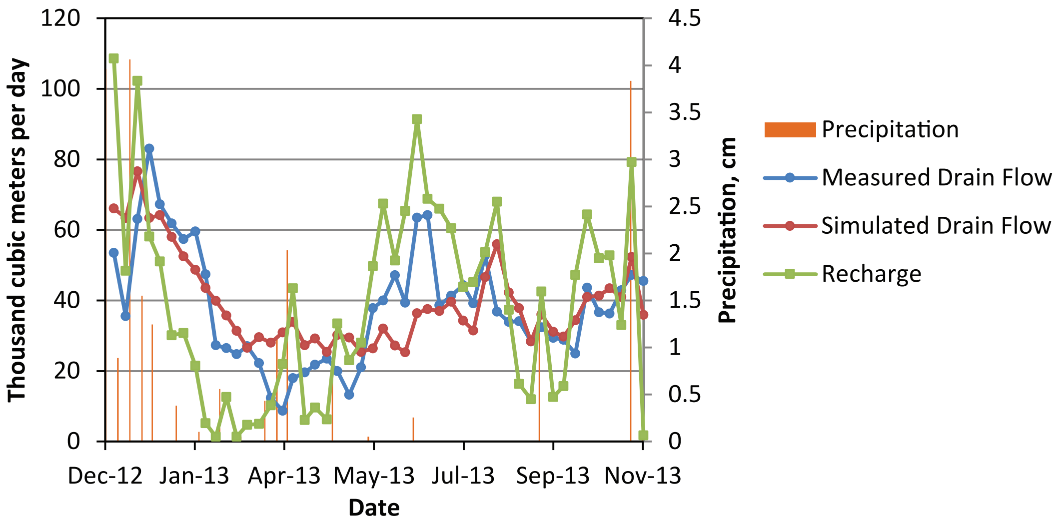

Figure 9 Measured and simulated drain flow, simulated recharge, and measured precipitation, December 2012–November 2013

during the 1-year simulation period (Figure 9) were 38,100 $m^3 d^{-1}$ and 39,300 $m^3 d^{-1}$, respectively (3.1% difference). In summary, the analysis of the suite of indicators of model performance demonstrates that model output was minimally influenced by model errors.

The steady-state groundwater budget (Table 3A); consists of seepage to and from adjacent channels, precipitation recharge, evapotranspiration (see Appendix B), and drainage discharged from the island. Seepage from the adjacent channels is the primary inflow (38,900 $m^3 d^{-1}$) and drain flow represents the primary outflow (45,700 $m^3 d^{-1}$). The transient model water budget (Table 3B) also includes changes in groundwater storage. The majority of the inflow for the transient simulation is from irrigation and precipitation recharge (38,800 $m^3\,d^{-1}$). Evapotranspiration represents 29% of total outflow and drain flow represents 54% of the total outflow.

Solute-Transport Model Results

Drain DOC loads simulated by the solute-transport model were similar to DOC loads calculated as the product of measured drain DOC concentrations and drain flow. During December 2012–March 2013, the average measured DOC load for the entire island was 749 $kg\,d^{-1}$, and the average simulated DOC load for this same period was 797 $kg\,d^{-1}$ – 6% greater than measured. The average measured DOC load over the transient period for the entire island was 637 $kg\,d^{-1}$, and the average simulated DOC load for this same period was 752 $kg\,d^{-1}$ – 18% greater than measured (Figure 10).

Table 3A Calculated daily groundwater budget for the steady-state Twitchell Island groundwater-flow model

Budget component	Inflow ($m^3\,d^{-1}$) (% of budget)	Outflow ($m^3\,d^{-1}$) (% of budget)	Net ($m^3\,d^{-1}$)
Seepage	39,500 (73%)	600 (1%)	38,900
Recharge	14,700 (27%)	—	14,700
Evapotranspiration	—	7,900 (15%)	–7,900
Drain flow	—	45,700 (84%)	–45,700
Total	54,200	54,200	0

Table 3B Calculated daily average groundwater budget for the transient Twitchell Island groundwater-flow model

Budget Component	Inflow ($m^3\,d^{-1}$) (% of budget)	Outflow ($m^3\,d^{-1}$) (% of budget)	Net ($m^3\,d^{-1}$)
Storage	11,700 (16%)	12,300 (17%)	–600
Seepage	21,900 (30%)	—	21,900
Recharge	38,800 (54%)	—	38,800
Evapotranspiration	—	20,800 (29%)	–20,800
Drain flow	—	39,300 (54%)	–39,300
Total	72,400	72,400	0

Evaluation of Effects of Land- and Water-Management Practices on Seepage, Drain Flow, and DOC Loads

Compared to BAU (Scenario 8), maintenance of higher groundwater levels for the alternative scenarios results in lower simulated seepage for all scenarios except Scenario 1 (rice on 324 ha) by a few percent to over 20% (Figure 11). The greatest decrease resulted when groundwater levels in drainage ditches were simulated at land surface for wetlands and rice in Scenarios 5, 6, and 7 (Table 1).

The highest drain flows occurred when drainage-ditch water levels were simulated near the bottom of ditches (Scenarios 3 and 4) (Figure 12). In contrast, when drainage-ditch water levels were simulated at land surface where wetlands were the dominant land use (Scenarios 6 and 7), drain flows were lower than for BUA. In Scenario 5, in which rice is the primary land use and drainage-ditch water levels were maintained at land surface, drain flow was 38% greater than the BAU scenario. The lowest drain flow occurs when wetlands dominate the island and drains are at land surface (Scenario 7). Similarly, drainage DOC loads were highest relative to BAU for Scenarios 3 and 4 (Figure 13) and lowest for Scenario 7. For Scenario 6, in which rice cultivation was simulated on the island periphery, DOC loads were approximately equal to the BAU scenario. In scenario 5, in which rice is the primary land use and drainage-ditch water levels were maintained at land surface, drain loads were over 100% greater than the BAU scenario.

Simulated subsidence to 2050 resulted in increased seepage, drain flow, and drain DOC loads of 10%, 6%, and 4% relative to 2013 conditions, respectively. Relative to this scenario, simulated seepage for all other scenarios was lower. The greatest decrease in seepage of 25% or more resulted when groundwater levels in drainage ditches were simulated at near land surface for wetlands and rice (Scenarios 5a, 6a and 7a) (Figure 11B). Similar to the 2013 scenario, relative to the 2050 BAU scenario, simulated drain flow was lower when drainage-ditch water levels were simulated as maintained at land surface (Scenarios 6a and 7a) (Figure 12B).

Under simulated permanently flooded conditions, Deverel et al. (2007b) indicated that DOC leaching will occur over several years, and DOC loads will decrease for permanently flooded conditions. Results from the Twitchell Island wetland ponds indicated that the organic soils are the major source of DOC, and that groundwater DOC concentrations decreased with time during permanent flooding (Fleck et al. 2007). Disinfection byproduct concentrations as indicated by THMFP formation were highly correlated with DOC in Twitchell Island drain water and groundwater samples ($R^2 = 0.96$) (Deverel et al. 2007a); therefore, DBP loads will generally follow changes in DOC loads.

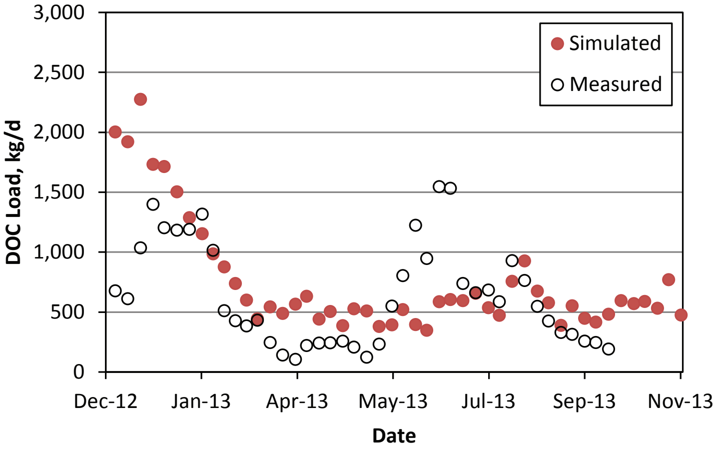

Figure 10 Measured and simulated DOC loads, December 2012 through November 2013

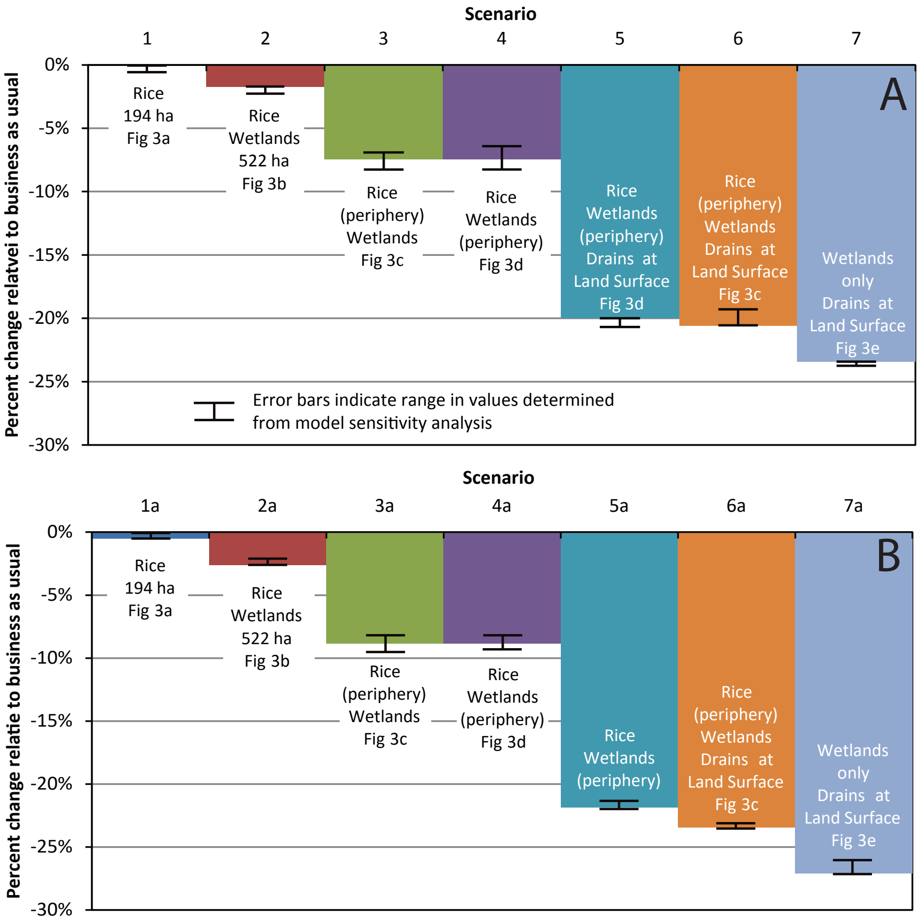

Figure 11 Comparison of simulated seepage for land-use and water-management scenarios relative to business-as-usual for 2013 **(A)** and 2050 **(B)** conditions

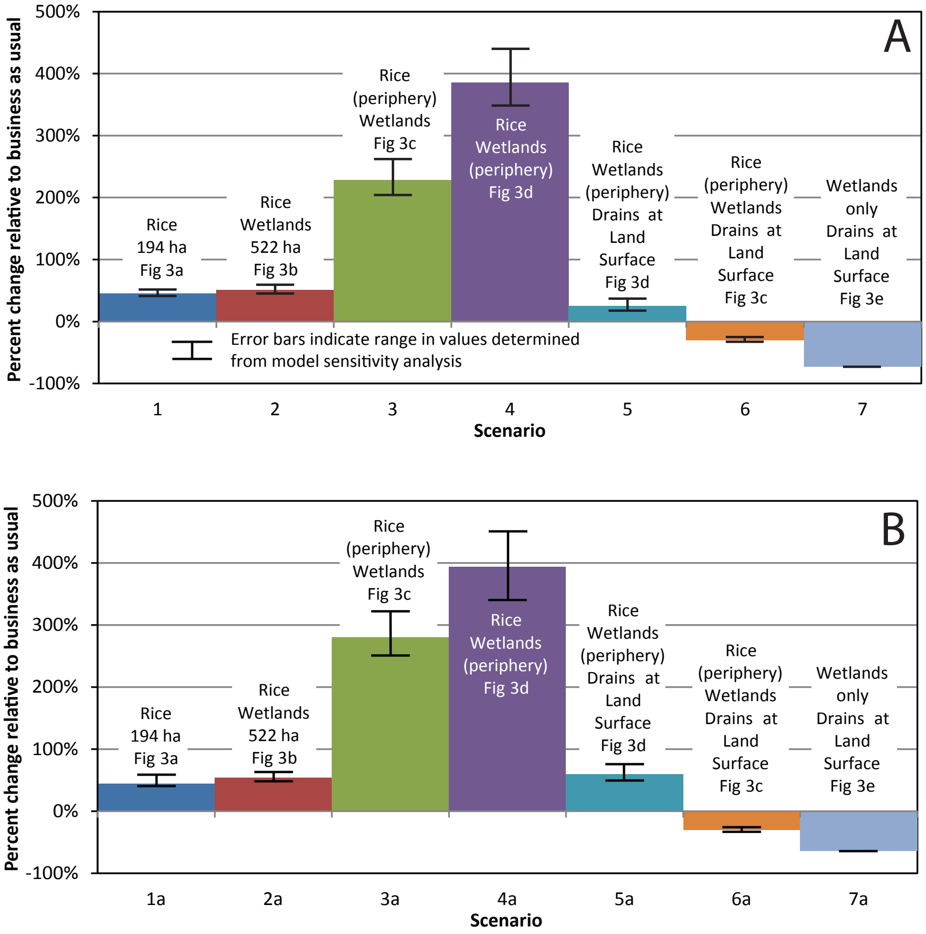

Figure 12 Comparison of simulated drain flow for land-use and water-management scenarios relative to business-as-usual for 2013 **(A)** and 2050 **(B)** conditions

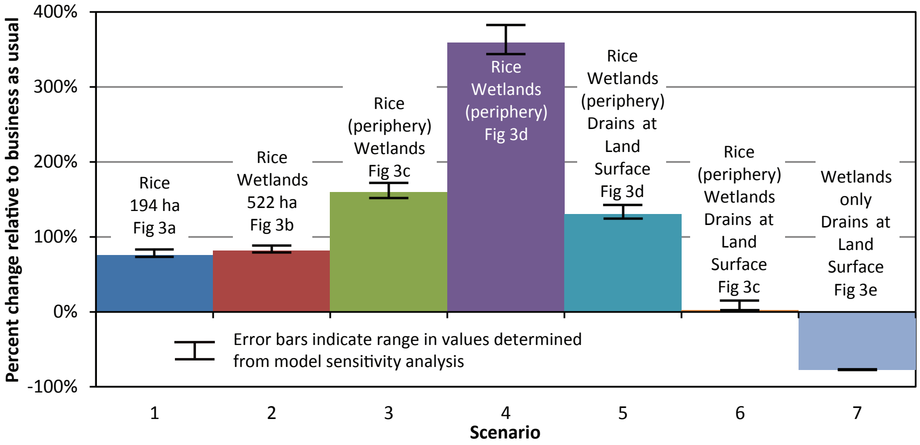

Figure 13 Comparison of simulated DOC loads for land-use and water-management scenarios relative to business-as-usual for 2013 conditions

DISCUSSION

The area of deep and active subsidence presents unique challenges to Delta sustainability. Alternative land uses such as rice and wetlands that stop or reverse the effects of subsidence will enhance sustainability but also present additional challenges: potential water quality effects, infrastructural investment, potential loss of agricultural income, and drainage. Implementation of these alternative subsidence-mitigating land uses requires quantitative understanding of the effects on drainage volumes and loads of DOC and DPBs, and ways in which water quality effects can be minimized. Our work improved understanding of these effects and answered important questions.

Our results suggest that water quality concerns can be mitigated through hydrologic controls that minimize export of DOC and DBPs from subsided islands. Subsidence mitigation resulted in reduced seepage in all cases. Only by maintaining drain elevations at land surface did our results show a minimal increase or decrease in drain flow and DOC loads relative to BAU scenarios. These measures will likely also mitigate methyl mercury exports (Heim et al. 2009), reduce levee vulnerability (Deverel et al. 2016b), and result in a net greenhouse emissions reductions (Knox et al. 2015). Results from the Twitchell Island rice project demonstrated the minimization of DOC and methylmercury exports through recirculation of drainage water (Deverel et al. 2013).

Implementation of these alternative land uses requires additional practical considerations. Substantial one-time infrastructural investments for earth moving as well as revised drainage and water delivery systems are required. Accumulated salinity may require periodic flushing and release of drainage water to adjacent channels. Drainage can be challenging where rice and wetlands are implemented in conjunction with other crops that require a drained root zone; drainage ditches will be the primary mitigation mechanism. Weed control in rice where there are neighboring traditional crops may also negatively affect yields because herbicide application, which may damage adjacent crops, will be limited by wind and air temperature. Delta rice yields are comparable with those in the Sacramento Valley, and rice has generally been profitable for Delta growers for the last 10 to 20 years. With the recent development of the carbon methodology for Delta wetlands (Deverel et al. 2017a), income is also available for demonstrated greenhouse gas emissions reductions in managed, permanently flooded wetlands and rice. Assessment of implementation of a mosaic of traditional crops (on low organic matter soils) and wetlands and rice (on high organic matter soils) on Staten Island demonstrated substantial greenhouse gas reduction benefit and profitability comparable with the status quo (Deverel et al. 2017b). Such a mosaic could be applicable on other Delta islands. Habitat benefits in rice for foraging and roosting have been demonstrated for threatened species such as the Greater Sand Hill Crane (Littlefield 2002; Ivey et al. 2011; Shaskey 2012). Such a mosaic would also offer opportunity for reuse of drainage water and thus minimization of DOC and methylmercury exports.

Uncertainty

The primary model limitations result from the limited spatial distribution of water level data and the lack of data for some model inputs, primarily recharge and hydraulic conductivity. Water level data is available primarily for the central and southeast part of the island. Results of the sensitivity analysis indicate that the model is most sensitive to recharge, evapotranspiration rate, horizontal hydraulic conductivity of Layer 1, Layer 2, Layer 5, and the horizontal hydraulic conductivity of the levee material in Layer 5. The effects of these model inputs on the evaluation of the effects of land- and water-management practices on drain flow, seepage, and DOC loads are reflected in the error bars on Figures 11, 12, and 13. The range of the error bars is relatively small compared to the differences in many scenarios, indicating that the uncertainty in the most sensitive model inputs does not substantially affect the evaluation and comparison of the effects of the land- and water- management practices.

SUMMARY AND CONCLUSIONS

Using groundwater-flow and solute-transport modeling, and the conceptual model and data

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described herein and in Deverel et al. (2007a, 2007b), we developed steady-state and transient groundwater-flow and solute-transport models for Twitchell Island. We answered important questions about the implementation of alternative subsidence-mitigating land uses as follows.

1. How do the groundwater-flow and drainage systems interact to influence island drainage volumes and drain DOC concentrations and loads?
2. How will future subsidence affect drainage volumes, DOC loads, and seepage onto islands?
3. How will land-use changes to mitigate subsidence affect seepage, drain flow, and DOC loads?
4. How can water-quality effects from drainage, restoration, and rice cultivation on Delta islands be minimized?

We used substantial hydrologic and water-quality data to characterize groundwater/drain interactions, estimate transmitting properties of island sediments, understand DOC and DBP concentrations and loads, and develop models. Modeling results agree well with measured water levels, island and individual drain flows, and DOC loads. The data for Twitchell Island and other Delta islands demonstrate the importance of subsurface processes in determining DOC and DBP concentrations and loads, and the interaction of surface water and groundwater. The hydrology of Twitchell Island is typical of subsided Delta islands in which water from adjacent channels seeps onto the islands and a network of drainage ditches captures shallow groundwater to be discharged to surface water bodies.

Future subsidence and sea level rise will cause increasing drain flows and DOC loads. Alternative land uses such as rice and wetlands will stop or reverse the effects of subsidence and thus reduce seepage onto islands. However, our work indicates that drain flow and DOC loads for these alternate land uses can be reduced through hydrologic controls that minimize the export of drainage water. Our extensive experience, and data collected throughout the Delta, demonstrate that these results for Twitchell Island are applicable for all subsided Delta islands, and analysis and models presented here provide useful tools to evaluate the effects of implementing alternative land uses.

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