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Abstract:
We used available data to estimate changes in land use and wet, non-farmable, and marginally farmable (WNMF) areas in the Delta from 1984 to 2012, and developed a conceptual model for processes that affect the changes observed. We analyzed aerial photography, groundwater levels, land–surface elevation data, well and boring logs, and surface water elevations. We used estimates for sea level rise and future subsidence to assess future vulnerability for the development of WNMF areas. The cumulative WNMF area increased linearly about 10-fold, from about 274 hectares (ha) in 1984 to about 2,800 ha in 2012. Moreover, several islands have experienced land use changes associated with reduced ability to drain the land. These have occurred primarily in the western and central Delta where organic soils have thinned; there are thin underlying mud deposits, and drainage ditches have not been maintained. Subsidence is the key process that will contribute to future increased likelihood of WNMF areas by reducing the thickness of organic soils and increasing hydraulic gradients onto the islands. To a lesser extent, sea level rise will also contribute to increased seepage onto islands by increasing groundwater levels in the aquifer under the organic soil and tidal mud, and increasing the hydraulic gradient onto islands

from adjacent channels. WNMF develop from increased seepage under levees, which is caused by changing flow paths as organic soil thickness has decreased. This process is exacerbated by thin tidal mud deposits. Based primarily on projected reduced organic soil thickness and land–surface elevations, we delineated an additional area of about 3,450 ha that will be vulnerable to reduced arability and increased wetness by 2050.

Supporting material:

Appendix A: WNMF Area Mapping
Appendix B: Groundwater Levels, Borehole Lithological Data, and Thickness of Organic Soils and Mud Deposits

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Evolution of Arability and Land Use, Sacramento–San Joaquin Delta, California

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ABSTRACT

We used available data to estimate changes in land use and wet, non-farmable, and marginally farmable (WNMF) areas in the Delta from 1984 to 2012, and developed a conceptual model for processes that affect the changes observed. We analyzed aerial photography, groundwater levels, land–surface elevation data, well and boring logs, and surface water elevations. We used estimates for sea level rise and future subsidence to assess future vulnerability for the development of WNMF areas.

The cumulative WNMF area increased linearly about 10-fold, from about 274 hectares (ha) in 1984 to about 2,800 ha in 2012. Moreover, several islands have experienced land use changes associated with reduced ability to drain the land. These have occurred primarily in the western and central Delta where organic soils have thinned; there are thin underlying mud deposits, and drainage ditches have not been maintained.

Subsidence is the key process that will contribute to future increased likelihood of WNMF areas by reducing the thickness of organic soils and increasing hydraulic gradients and seepage onto the islands. To a lesser extent, sea level rise will also contribute to increased seepage onto islands by increasing groundwater levels in the aquifer under the organic soil and tidal mud, and increasing the hydraulic gradient onto islands from adjacent channels.

WNMF areas develop from increased seepage under levees, which is caused by changing flow paths as organic soil thickness has decreased. This process is exacerbated by thin tidal mud deposits. Based primarily on projected reduced organic soil thickness and land–surface elevations, we delineated an additional area of about 3,450 ha that will be vulnerable to reduced arability and increased wetness by 2050.

INTRODUCTION

Subsidence and sea level rise can affect the long-term viability of traditional agriculture on organic and highly organic mineral soils (hereafter organic soils) in the Sacramento–San Joaquin Delta. Consequences of subsidence and sea level rise include increasing hydraulic gradients and seepage onto Delta islands (Deverel et al. 2007b) and decreasing levee stability (URS Corporation and Jack R. Benjamin & Associates, Inc. 2008). Island drainage export loads of dissolved organic carbon and methyl mercury to Delta channels may also increase (Deverel et al. 2007b; Heim et al. 2009), and drainage costs will increase because of larger pumping lifts. To maintain an aerated root zone, networks of drainage ditches collect groundwater and discharge it to adjacent channels. The total volume below sea level on Delta islands will continue to increase with decreasing elevations and sea level rise. When islands flood, saline water can be drawn into the Delta, jeopardizing water supply and water quality for agriculture (e.g., Cook 1973).

Anecdotal evidence indicates that subsidence-induced seepage has increasingly become an impediment to farming on Delta islands because of increased wetness. Because of the potential for future reduction in Delta agricultural acreage, we sought to answer key questions about areas of greater wetness and reduced arability. Delta agricultural revenues total over $790 million, which represents a significant source of employment (over 12,000 jobs), and billions of dollars in indirect benefits (DPC 2012). Future loss of Delta agricultural land from increasing seepage thus represents a potential socio-economic effect.

Key questions include:

- How has farming historically been affected?
- What spatially and temporally variable processes and features affect the formation of wet, non-farmable, and marginally farmable (WNMF) areas and land-use changes?
- What areas will be affected in the future?

Our overall objective was to define processes and factors that affect historic and future reduced arability of Delta organic soils. These include island–surface elevation, hydraulic gradients between island groundwater and adjacent channels, and subsurface lithology. We (1) delineated areas and time-frames for historic increases in WNMF acreage relative to the processes and factors that influenced the increases and (2) attempted to delineate areas vulnerable to reduced arability in the future.

Subsurface lithology, a key factor that affects seepage, reflects processes that occurred at the confluence of major river systems, floodplains, and tidal wetlands during the Quaternary and Holocene. These processes resulted in a vertical sequence of organic deposits that overlay tidal mud, floodplain, and alluvial fan deposits and eolian sands. We hypothesized that the spatially variable thicknesses of tidal mud and organic soil influences the extent of seepage, and thus reduced arability. (Atwater [1980] defined tidal mud as silt and clay underlying the organic soil.) We therefore sought to define the spatial distribution of mud and organic soil thickness, and identify geomorphic processes that affect their spatial distribution in relation to mapped WNMF areas.

Tidal mud accumulated under relatively lower stream velocities at the distal areas of alluvial fans and in tidal floodplains. In the Delta, tidal muds were primarily deposited during sea level rise of about 1 to 2 mm yr^{-1} which began about 11,000 years ago (Atwater 1980) and resulted in the arrival of tidal waters to the elevation of the Delta shallow lands and waterways about 7,000 years ago. Slowing sea level rise during the last 6,700 years allowed marshes and wetlands to form under anaerobic conditions (Atwater 1982). Decaying wetland plants mixed with sediment influx and resulted in the formation of a 1,400 km^2 area of tidal freshwater marsh and about 4.5 million cubic meters of organic soils (Shlemon and Begg 1975; Atwater et al. 1977; Mount and Twiss 2005; Drexler et al. 2009; Deverel and Leighton 2010).

Subsidence began during the late 1800s and early 1900s when most of the Delta was levied and drained for agriculture (Thompson 1957). The primary cause of subsidence is microbial oxidation of organic soils (Deverel and Rojstaczer 1996; Deverel and Leighton 2010). Subsidence rates decreased over time because of changing land management practices and decreasing soil organic-matter content. Estimated present-day rates generally range from less than 0.5 to over 3 cm yr^{-1} (Deverel and Leighton 2010). Deverel and Leighton (2010) predicted about 1.4 m of subsidence by 2050 in the central Delta where soils have the highest organic matter content. They predicted less elevation loss in the western, northern and southern Delta where organic matter content is generally lower than the central Delta. Sea level rise and subsidence will increase the volume below sea level by about 346,956,000 m^3 (281,300 af) by 2050 (Deverel and Leighton 2010). Subsidence rates are significantly correlated with soil organic matter content (Rojstaczer and Deverel 1995; Deverel and Leighton 2010). Regionally, soil organic matter content, organic soil thickness, and subsidence have been influenced by the amount of time since initial drainage, and the pre-development depositional environment (Deverel and Leighton 2010).

To analyze and assess the effects of interacting processes and factors that affect the evolution of WNMF areas, we processed and analyzed aerial photos and land use data, in relation to land–surface elevation, subsurface lithology, groundwater hydraulics, subsidence, and sea level rise. The primary geographic area of interest includes about 81,000 ha (200,000ac) of organic soils shown on Figure 1 in Deverel and Leighton (2010). We also used available data and models to delineate areas where WNMF areas are likely to develop during the next 50 years.

METHODS AND DATA SOURCES

Google Earth and U.S. Geological Survey (USGS) infrared imagery and land use maps were used to delineate WNMF areas and land use changes through time. To better understand factors that affect the distribution of WNMF areas: (1) land surface elevations were mapped, (2) groundwater levels and stage data were used to calculate hydraulic gradients, (3) borehole data and geostatiscal mapping were used to estimate organic soil and mud thicknesses, (4) a groundwater flow model was used to assess changes in groundwater hydraulics over time, and (5) the subsidence model SUBCALC was used delineate areas vulnerable to changes in arability. We also visited specific WNMF areas and spoke with growers and farm managers. Methods and data sources details are described below. A Geographic Information System (GIS) was used to integrate and synthesize information and data.

Aerial Photos and Land Use Maps and Delineation of Areas of Reduced Arability

Google Earth displays satellite images of varying resolution of the Earth's surface. We used historical Google Earth images from 1993 through 2012 at approximately 1-m resolution. Some challenges exist for using Google Earth because of its limited spectra (red green and blue bands). However, numerous authors have documented the effectiveness of the Google Earth platform for documenting land use variation (e.g. Fritz et al 2009; Hu et al 2013) We also examined historical aerial photos, National Aerial Photography Program (NAPP) images, and National High Altitude Photography (NHAP) images available from the USGS database for 1970, 1974, 1984, and 1987. (*http://earthexplorer.usgs.gov/*) at scales of 1:40,000 and 1:58,000, respectively. We carefully scrutinized the aerial images for each island. By identifying the signature for WNMF areas based on images of known WNMF areas, we then searched for similar signatures in other locations, and verified selected WNMF areas with landowners and growers. Appendix A contains detailed information and example aerial images for delineating WNMF areas.

Since 1976, land use has changed on many Delta islands; therefore, we obtained land-use survey GIS shape files from the California Department of Water Resources (CDWR) for 1976, 1991, and 2007 to assess these changes (*http://www.water.ca.gov/landwateruse/lusrvymain.cfm*). The CDWR developed these maps from aerial photographs, satellite imagery, and field site visits. We summed acreages by class to assess land-use trends.

Land Surface Elevations

Land surface elevations were based on LiDAR (Light Detection and Ranging) data the CDWR collected in January and February of 2007.

Groundwater Levels

To assess groundwater levels, we used groundwater level measurements collected from 1989 through 2012 under various projects and data sources. Appendix B contains information on groundwater levels.

Delta Channel Stage and Sea Level Rise

We obtained river stage data from ten gauge stations from 2009 to 2012 operated by CDWR (*http://www.water.ca.gov/waterdatalibrary/*) and the USGS (*http://cdec.water.ca.gov/*). For each station, we calculated daily average stage and average daily high water stage. We assumed that projected average sea level rise estimated from 2010 to 2050 by Cayan et al. (2009) and Vermeer and Rahmstorf (2009) applied directly to Delta surface-water elevations. Therefore, each year's incremental sea level rise was added to the 2009–2012 daily stage average and mean-high stage values to estimate future average stage and mean-high stage at each station.

Borehole Lithological Data and Thickness of Organic Soils and Mud Deposits

We obtained well and bore-hole logs from the Delta Wetlands Project (Harding Lawson Associates 1991; Hultgren–Tillis 1995), the 2004 Jones Tract Flood Report (Hultgren–Tillis 2005) and from the CDWR (2012 data transfer set to Christina Lucero from Joel Dudas, unreferenced, see "Notes"). These data, and data presented in Atwater (1982), were used to define the bottom elevation of the organic and mud deposits. (See Appendix B for more information on borehole lithology data sources.)

To characterize the spatial distribution of the organic-soil-bottom and mud-bottom elevations and thickness as related to geomorphic processes and the WNMF areas, we used the theory of regionalized variables or geostatistics and Geostatistical Analyst within ArcGIS to create mud bottom and organic-soil-bottom elevation grids. The theory of regionalized variables as described by Matheron (1963), David (1977), Journel and Huijbregts (1978) and others relies on the description of data collected in geographic areas as randomly distributed. "Kriging," the process of interpolation from measured values at various locations relies on the determination of the spatial covariance or semivariogram of the variable at all defined points.

Appendix B contains detailed information about the methods taken to create the tidal mud bottom and organic-soil bottom elevation grids using kriging. After creating a grid of estimated organic-soil-bottom and mud-bottom elevations by kriging, we created a mud thickness map by subtracting the mud bottom elevation grid from the organic-soil-bottom elevation grid in GIS. Similarly, we created an organic-soil thickness map by subtracting the organic-soil-bottom elevation grid from the LiDAR land surface elevation grid (CDWR 2007), which is reported in NAVD-88.

Hydraulic Gradients from Delta Channels to Islands

As land–surface elevations decrease and sea level rises, hydraulic forces that cause seepage under levees via mineral sediments to drainage ditches at the base of levees (toe drains) will increase. Under-seepage exit hydraulic gradients in drainage ditches indicate the potential for increased under-seepage that may result in excessive wetness in the adjacent organic soil and reduced arability. To estimate under-seepage exit gradients, it is essential to know or estimate the hydraulic head in the confined aquifer that underlies the organic soil. We estimated exit gradients in toe drains where these data were available.

We assumed that the reported depth to groundwater measurements adequately represents current conditions. (See Appendix B for the rationale for this assumption.) We calculated the exit gradient at drainage ditches for present-day ground surface conditions as follows:

$$Exit\ gradient = \frac{\left(WLE_{td} - WLE_{ua}\right)}{D} \tag{1}$$

where WLE_{td} and WLE_{ua} are the water level elevations in the toe drain and underlying aquifer, respectively, and D is the vertical distance from the drainage ditch bottom to the bottom elevation of the organic soil.

Where data were unavailable, we approximated the drainage ditch as being 1.2 to 1.8 m below the land surface elevation, with 0.15 to 0.6 m of water in the ditch. At selected locations we determined the depth of the drainage ditch and water levels. At each location, we obtained average land–surface elevation using the 2007 LiDAR data (CDWR 2007), and the estimated organic soil bottom elevation was used, as described above.

Groundwater Flow Model

We used the Twitchell Island groundwater-flow model originally developed by Deverel et al. (2007b), which simulated steady-state groundwater flow of winter 2003 conditions, to help assess the effect of subsidence on seepage processes. The USGS numerical finite-difference groundwater-flow model (MODFLOW) (McDonald and Harbaugh 1988) was used to simulate the distribution of hydraulic heads and volumetric fluxes. The model was developed and calibrated for average groundwater levels and drain flows measured from December to March 2003. Model details are available in Deverel et al. (2007b) and are briefly summarized here.

The model consists of five layers with variable thicknesses representing different stratigraphic units as follows: Layer 1, shallow most oxidized organic soils; Layers 2 and 3, less oxidized organic soils; Layer 4, fine grained clay and silt deposits; and Layer 5, underlying silty sands and fine to coarse sands which extend to 18 m below sea level. Boundary conditions included specified heads around the edge of the island to represent average channel stage elevation and a no-flow boundary at the bottom of the model. Drainage ditch water elevations were specified based on field measurements at selected drainage ditches, and the drains were simulated using the MODFLOW drain package.

Hydraulic conductivity was assigned based on soil types (Tugel 1993) and corresponding hydraulic conductivity measurements conducted within each soil type (Deverel et al. 2007b). The model was calibrated by adjusting horizontal and vertical hydraulic conductivity values within the range of measured values to minimize the difference between simulated and measured water levels and drain flows. Recharge values were estimated from soil–water budget calculations using daily precipitation and evapotranspiration measurements from Twitchell Island. Recharge in the wetland pond operated by the CDWR (Miller et al. 2008) was specified based on data reported in Gamble et al. (2003).

We modified the 2003 Twitchell model (Deverel et al. 2007b) to simulate 1910 conditions by raising the simulated land–surface elevation which was estimated from the 1910 USGS Jersey Island and Bouldin Island 7.5-min quadrangle topographic maps. Model layering was adjusted accordingly. Only three main drains were mapped on Twitchell Island in 1910; we assumed, therefore, that field drains were not mapped and used the drain configurations mapped on the 1952 USGS Jersey Island and Bouldin Island 7.5-min quadrangle topographic maps. We assumed the stage in these drains was approximately 1.2 m below land surface, and assigned the drain conductance values consistent with the 2003 model. We reduced the boundary-condition constant head values to account for an average of 0.2 cm yr^{-1} sea level rise between 1910 and 2003.

Hydraulic conductivity values and zones remained the same for both models. We inserted particles into toe drain cells in both models placed at intervals both vertically along the drain edge nearest the levee and along the bottom of the drain cell. We used MODPATH particle tracking (Pollock 1994) to simulate flow paths to the toe drains.

Estimation of Future Subsidence and Organic Soil Thickness

We used the computer model SUBCALC (Deverel and Leighton 2010) to predict future land–surface elevation changes. SUBCALC simulates subsidence from aerobic microbial oxidation of organic carbon and consolidation. To calculate future subsidence, we assumed that: (1) oxidation and consolidation are the only present-day and future causes of subsidence; (2) land use and water-management practices will generally not change; and (3) the subsidence rate is zero where or when the soil organic matter content is less than or equal to 2%, or rice or permanently flooded wetlands are present.

RESULTS

WNMF Areas and Land Use Changes

We closely examined USGS infrared images and Google Earth aerial photos taken in 1984 to 2012 to delineate WNMF areas (see Figures 1–5). There were about 274 ha in 1984 and about 2,800 ha in 2012; a 10-fold increase. Figure 6 shows a linear increase in cumulative area from 1984 to 2012. Table 1 delineates WNMF areas by year and Island. Selected WNMF areas were verified in the field or by phone with farmers and land managers (see Appendix A).

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Figure 1 Locations of WNMF areas in 1984 and 1987

Figure 2 Locations of WNMF areas in 1993

Figure 3 Locations of WNMF areas in 2002

Figure 4 Locations of WNMF areas in 2006

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Figure 5 Map showing locations of WNMF areas in 2012

In addition to development of WNMF areas, land use changes have also occurred since the 1970s as indicated by CDWR land use maps, notably on Sherman, Twitchell, Jersey, Bradford, Mandeville, Empire, Tyler, Holland, Bethel, and Hotchkiss as described below (Table 2).

On Sherman Island, there was a general shift from field, grain, and hay crops to pasture from 1976 to 2007. Pasture on Sherman Island is generally underlain by shallow groundwater. Similarly, on Twitchell Island, there was a general shift from grain, hay and field crops to pasture from 1976 to 2007. The land-use shifts on Twitchell and Sherman islands were likely and partially from ownership change because the State of California purchased these islands during the 1990s. Since then, leasees have farmed the land. Drainage ditches have not been universally well maintained.

On Bradford Island, CDWR maps showed a general shift from field crops to idle lands and native vegetation from 1976 to 2007. A key factor responsible for this shift was the inability to adequately drain the land. As organic soils disappeared, drainage ditches were excavated into eolian sands which were not sufficiently cohesive to prevent ditches from collapsing. Wet and high water table conditions led to conversion to pasture or reintroduction of native vegetation. Also, drainage ditches were not regularly excavated (2012 phone conversation with Brent Gilbert, farmer, with Steven Deverel, unreferenced, see “Notes”).

Jersey Island pasture increased between 1976 and 1991, and native vegetation generally increased between 1976 and 2007. Field crops, grains, and hay reportedly decreased between 1976 and 2007. CDWR reported a decrease in grain, hay, truck and berry crops, and an increase in native-vegetation acreage on Mandeville Island. On Empire Tract, pasture acreage increased between 1976 and 2007, and field, truck, and grain crops decreased. On Tyler Island, CDWR mapped an increase in riparian vegetation from 1976 and 1991 to 2007. Similarly, on Hotchkiss

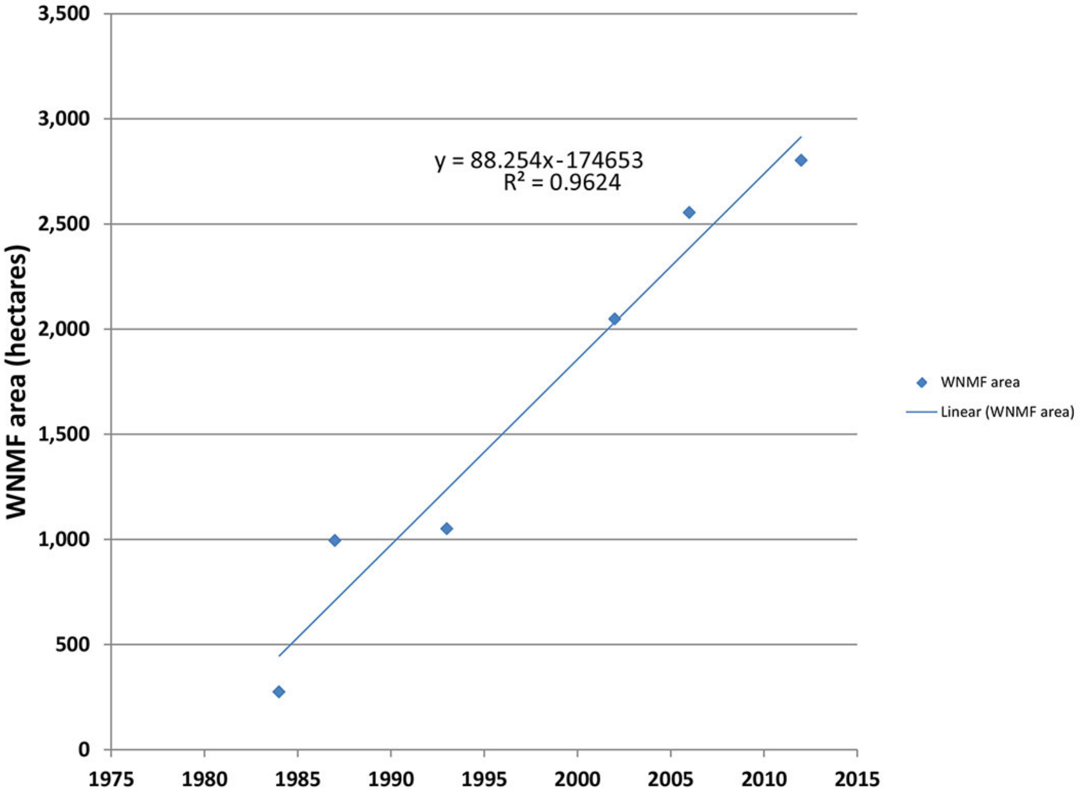

Figure 6 Temporal changes in cumulative WNMF area

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Table 1 Temporal changes in WNMF areas by island

	WNMF areas (ha)					
Island	**1984**	**1987**	**1993**	**2002**	**2006**	**2012**
Bacon		1.1	12.1	16.7	33.5	41.6
Bethel		72.1	64.5	84.8	67.0	59.3
Bishop			20.5	20.3	20.4	20.5
Bouldin	18.9	12.5	23.6	36.4	78.0	103.4
Bract		10.9		126.2	190.2	190.2
Bradford	75.2	69.1	141.8	258.0	250.6	318.8
Brannan–Andrus	38.1	26.1	41.7	76.7	92.2	95.8
Canal Ranch		10.3				6.0
Coney			1.8	1.8	1.6	7.0
Emerson			2.2	6.6	3.5	6.7
Empire		17.4	17.5	33.9	43.5	62.6
Grand		9.8	28.2	36.8	30.3	43.3
Holland		77.0	59.5	74.3	81.8	101.9
Hotchkiss		15.5	5.7	5.4	13.1	17.7
Jersey		25.8	23.1	13.4	50.3	37.6
Liberty			45.4			
Little Mandeville			4.6	7.7		
Lower Jones			2.0	3.8	15.8	14.2
Mandeville		42.2	63.3	121.4	264.7	190.2
McCormack–Williamson			10.9	16.9	16.0	15.4
McDonald		26.7	43.2	106.9	146.4	147.1
Medford		24.6	43.0	53.7	81.4	97.9
Merritt				0.6		
Neatherlands			8.3			
New Hope			13.5	11.6	15.8	17.2
Orwood			1.0	0.7	1.4	1.1
Other – no island classification		15.9				
Palm		12.5	3.7	31.8	26.2	29.2
Pierson		55.2	8.4	25.3	39.8	14.1
Prospect			3.7	43.0	173.6	173.4
Quimby		17.2	6.7	14.0	34.4	24.9
Rindge		5.0	0.3	4.0	5.3	5.9
Roberts		27.4	42.2	45.0	40.3	25.0
Ryer		4.4	6.2	6.4	7.9	49.1
Sherman	11.4	65.0	53.6	109.1	159.9	253.7
Shinkee		57.4		5.4		
Staten	8.8	6.3	4.9	5.2	7.0	5.4

Table 1 Temporal changes in WNMF areas by island *(continued)*

	WNMF areas (ha)					
Island	**1984**	**1987**	**1993**	**2002**	**2006**	**2012**
Stewart			3.0	0.8		1.2
Sutter		4.7				
Terminous		2.3	2.4	4.0	5.4	9.6
Twitchell	40.9		11.2	34.6	29.6	29.6
Tyler		19.9	15.8	363.3	221.8	222.1
Union			5.7	8.1	9.5	11.5
Upper Jones			2.8	5.9	18.3	10.4
Veale		35.3	0.5	1.2	1.2	1.0
Venice	23.9	79.2	67.5	83.6	92.7	132.5
Webb	57.3	146.1	117.0	123.9	147.3	182.9
Woodward			2.5	1.8	16.8	4.5
Wright–Elmwood			15.3	17.5	19.4	21.0
Total	274.4	995.1	1,050.6	2,048.6	2,553.9	2,802.7

Table 2 Selected land-use changes in hectares as mapped by CDWR for 1976, 1991, and 2007

Island and land use	1976	1991	2007	Apparent causal factors
Sherman field, grain and hay	3399	3367	778	Increasing wetness, land ownership change, lack of drainage ditch maintenance
Sherman pasture	358	154	2,640	
Twitchell field, grain and hay	1,191	1,116	571	Increasing wetness, land ownership change, lack of drainage ditch maintenance
Twitchell pasture	35	129	1,536	
Jersey native and riparian vegetation	446	295	592	Increasing wetness, land ownership change, lack of drainage ditch maintenance
Jersey pasture	783	1,135	692	
Jersey field crops, grain and hay	221	0	84	
Bradford field crops	476	0	0	Disappearance of organic soil, inability to maintain drainage ditches
Bradford native vegetation	264	71	581	
Mandeville grain, hay, truck, and berry crops	599	573	6	Disappearance of organic soil, increasing wetness
Mandeville native vegetation	277	164	1,231	
Empire native vegetation	200	92	168	Disappearance of organic soil, increasing wetness
Empire field and truck crops, grain and hay	1,295	1,395	1,133	
Empire pasture	0	0	70	
Tyler riparian vegetation	119	299	903	Increasing wetness
Hotchkiss native vegetation	143	254	340	Disappearance of organic soil, increasing wetness

Tract, mapped native vegetation increased from 1976 and 1991 to 2007.

Factors Affecting the Increased WNMF Area and Land Use Changes

Elevation, organic-soil and tidal-mud thicknesses, distance from the levee, and the presence of artesian conditions are key contributing factors to increased WNMF areas. The WNMF area locations predominate within 1,000 m of levees, where there are relatively thin organic soils and tidal mud, and elevations are below –2 m (Figure 7). Most of the WNMF areas were mapped where the organic soil thickness is less than 3 m (Figure 8). Some areas in the western and north western Delta were mapped where the organic soil thickness is 6 m or less, such as Grand Island, where the WNMF areas overlie organic soil ranging from 4.6- to 6-m thick.

Estimated tidal mud thickness (Figure 9) generally ranges from 0 to 6 m throughout the Delta. In the western to central western Delta, primarily on Brannan–Andrus and Bouldin islands, estimated mud thickness generally ranges from 3 to 8 m. Southern Sherman Island is underlain by mud thicknesses ranging from 5 to 11 m. Throughout the southwestern Delta, including the area predominated by eolian deposits, estimated mud thicknesses are consistently less than 3 m, and mostly less than 1.5 m. WNMF areas were mapped in or adjacent to the eolian areas on Bradford Island, Webb Tract, Holland Tract, and Bethel Island. As organic soils oxidized, the eolian dunes became visible on these islands. WNMF areas on Twitchell and Jersey islands overlie tidal mud deposits less than 1.5 m thick. WNMF, native vegetation, and riparian areas on Tyler, Grand, Bouldin and Venice islands and Empire Tract overlie or are adjacent to areas where the estimated tidal mud thickness is estimated to be less than 3 m.

Figure 10 shows histograms for the four key causal factors associated with WNMF areas. Elevations for most of the 2012 WNMF areas were equal to or less than –2 m (Figure 7). Of the 1,470 individual WNMF areas, 1,190 (81%) were at or below –2 m. Of the total 2,800-ha area in 2012, 2,050 ha (73%) were at or below –2 m. Fifty percent of the WNMF areas (1,400 ha) were within 500 m of levee crowns, and 82% (2,300 ha) were within 1,000 m of levee crowns. Fifty-eight percent (1,364 ha) of the WNMF area was underlain by organic soil thinner than 3 m, and 78% (1,835 ha) was underlain by organic soil thinner than 4.6 m. Seventy-eight percent of the area (1,810 ha) was underlain by tidal mud thicknesses equal to or less than 3 m.

Because of spatial uncertainty in the variables shown in Figure 10, we sought greater explanation of causality by aggregating areas by island. For the region at or below –2 m, we summed the area for each island and calculated the fraction of the island that was WNMF in 2012. Figure 11 shows the relation of the fraction of the island area to elevation for 27 islands where the average elevation was equal to or less than –2 m in 2007. Two islands, Bradford and Medford, contained large percentages mapped as WWMF (35% and 18%, respectively). Less than 10.3% of the areas on the 25 remaining islands (Bacon, Bethel, Bouldin, Bract, Brannan–Andrus, Emerson, Empire, Grand, Holland, Jersey, Lower Jones, Mandeville, McDonald, Orwood, Palm, Rindge, Roberts, Sherman, Terminous, Twitchell, Tyler, Upper Jones, Venice, Webb, and Woodward) were mapped as WNMF. For these islands, elevation explains 23% of the variance in percent of the island that is WNMF; additionally, the majority of the WNMF areas on these islands are underlain by 3 m or less of organic soil (Figure 8). The exceptions are Twitchell, Sherman, and Grand islands which generally contain small WNMF areas (1.8%, 5%, and 0.3%, respectively). Average estimated tidal mud thickness underneath WNMF areas on all 27 islands was less than 3.8 m (Figure 9) and for half of the islands, it was less than 1.5 m. Tidal mud was thickest underneath the WNMF areas on Brannan–Andrus (Figure 9) where only 0.3% of the island was WNMF in 2012.

Figure 12 shows the intersection of the three key factors—elevation ≤ –2 m, organic soil thickness ≤ 4.6 m, and mud thickness ≤ 3 m—this area encompasses 43% of the total WNMF area. The density of the WNMF areas in the shaded intersection area of 0.04 ha ha^{-1} (Figure 8), is greater than the surrounding area. The density of WNMF areas outside the shaded intersection area, which includes only the area of the legal

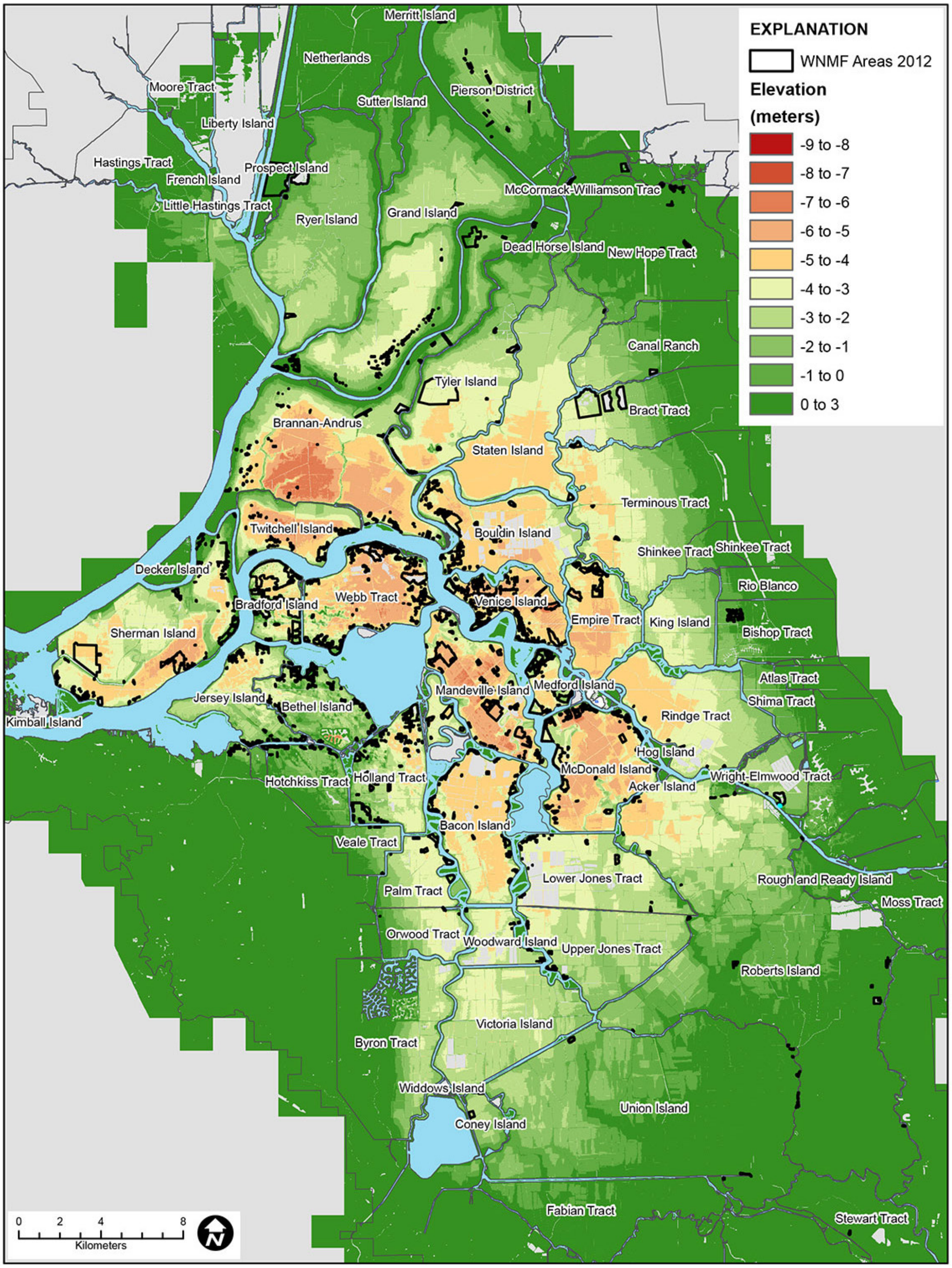

Figure 7 Locations of WNMF areas in 2012 and 2007 land–surface elevations

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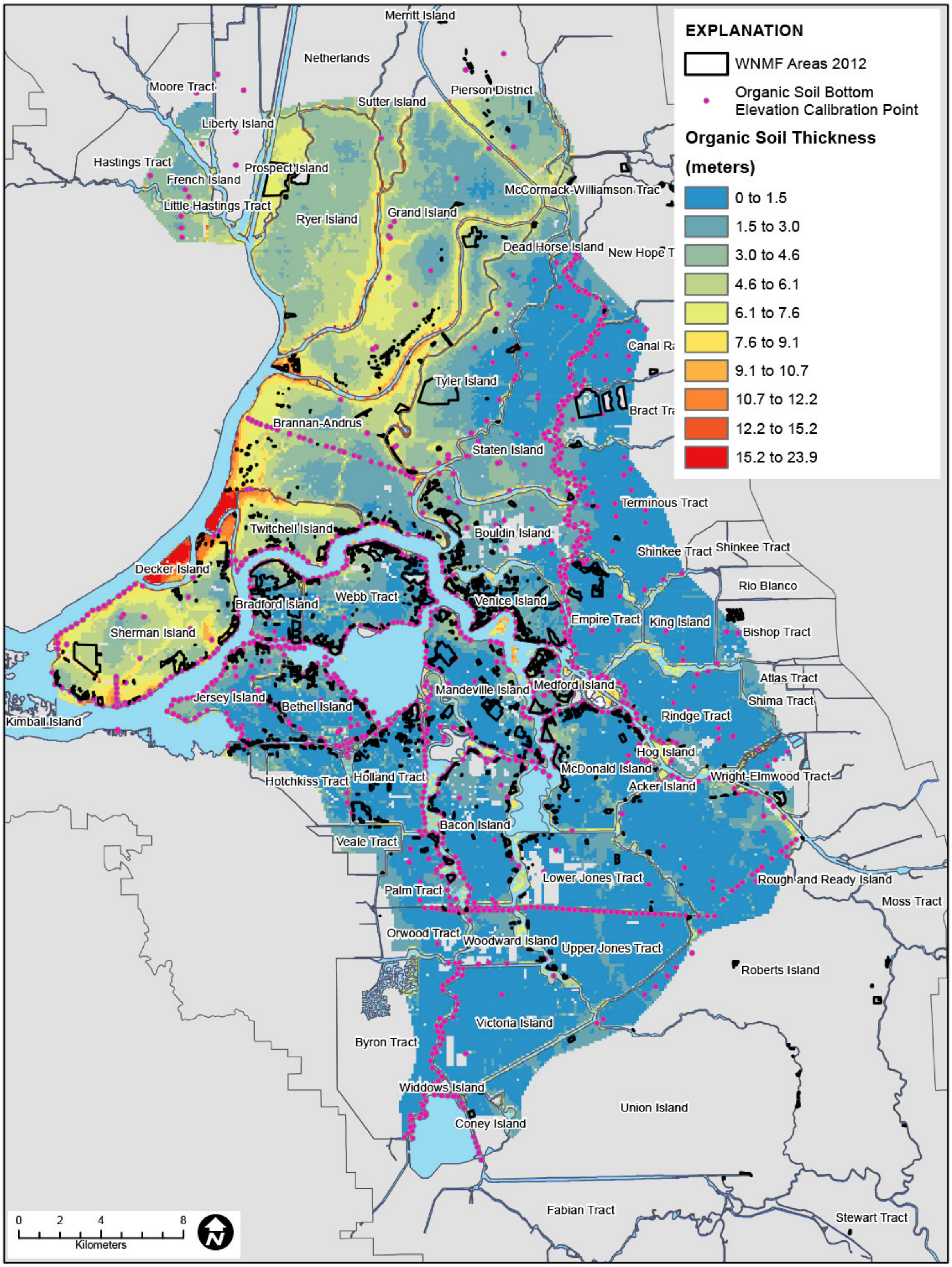

Figure 8 Locations of WNMF areas in 2012 and estimated organic soil thickness

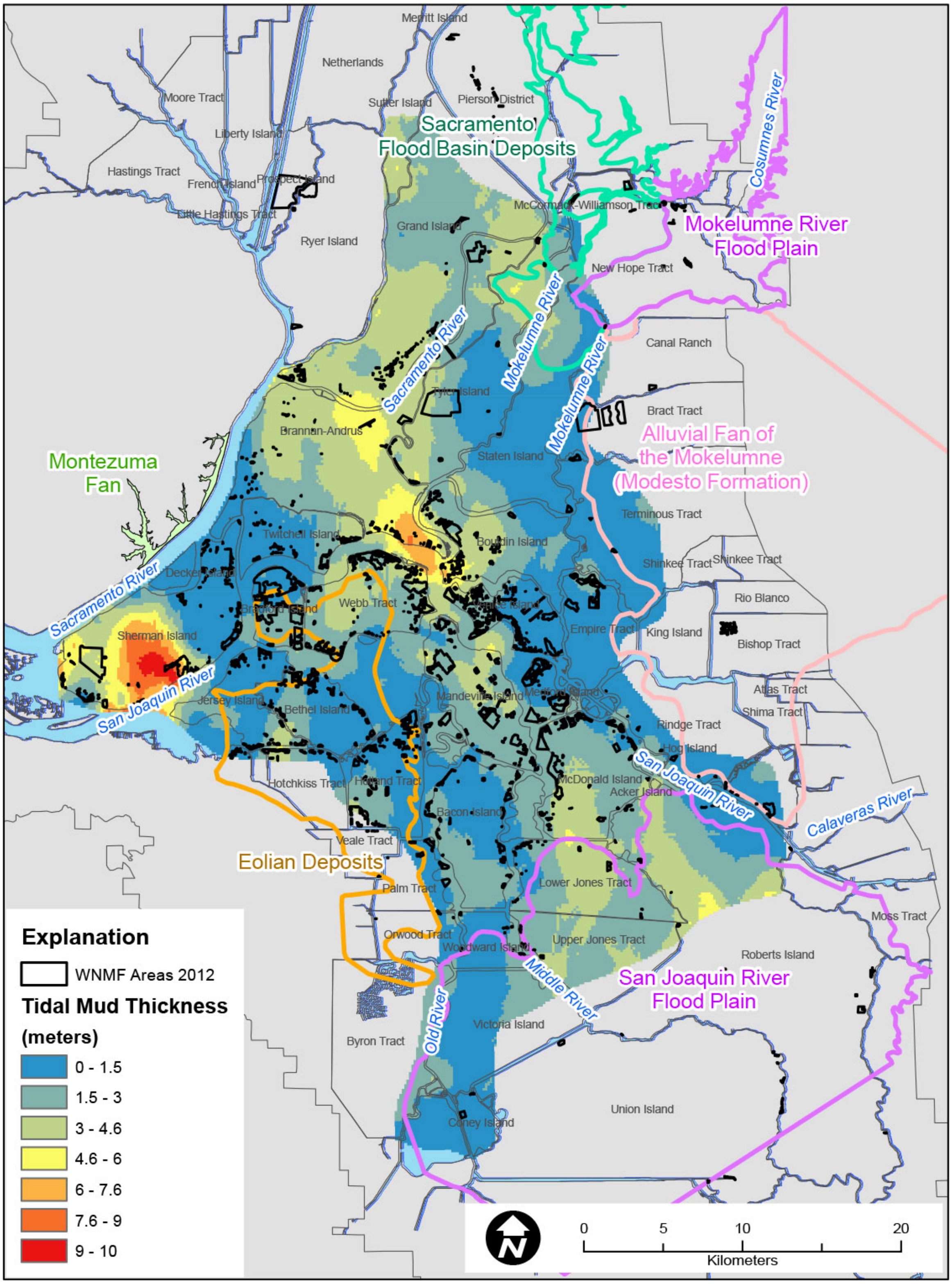

Figure 9 Locations of WNMF areas in 2012, estimated tidal mud thickness, and relevant geomorphic boundaries

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Figure 10 Histograms for 2012 WNMF areas: **(A)** elevation, **(B)** average distance from levee, **(C)** organic soil thickness, and **(D)** tidal mud thickness

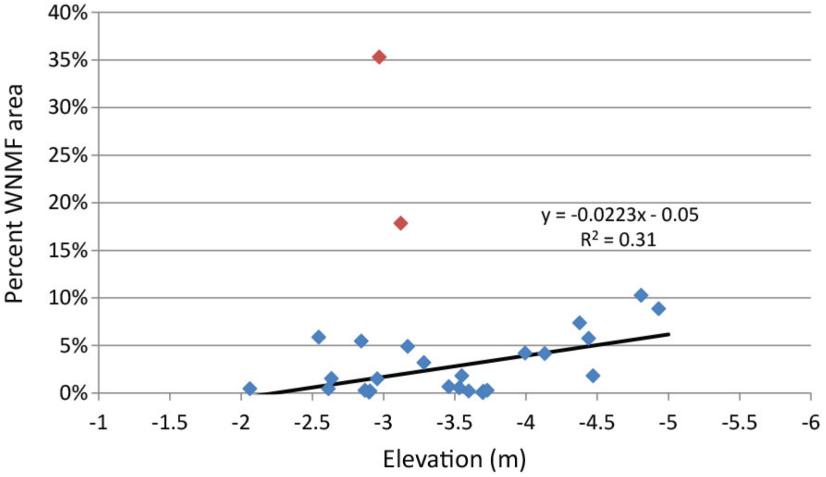


Figure 11 Relation of percent WNMF area on central Delta islands to elevation. WNMF areas included in the regression analysis were located where average elevation is less than or equal to –2 m. Bradford and Medford islands (35.3% and 17.8%, respectively, shown in red) are excluded from the regression analysis.

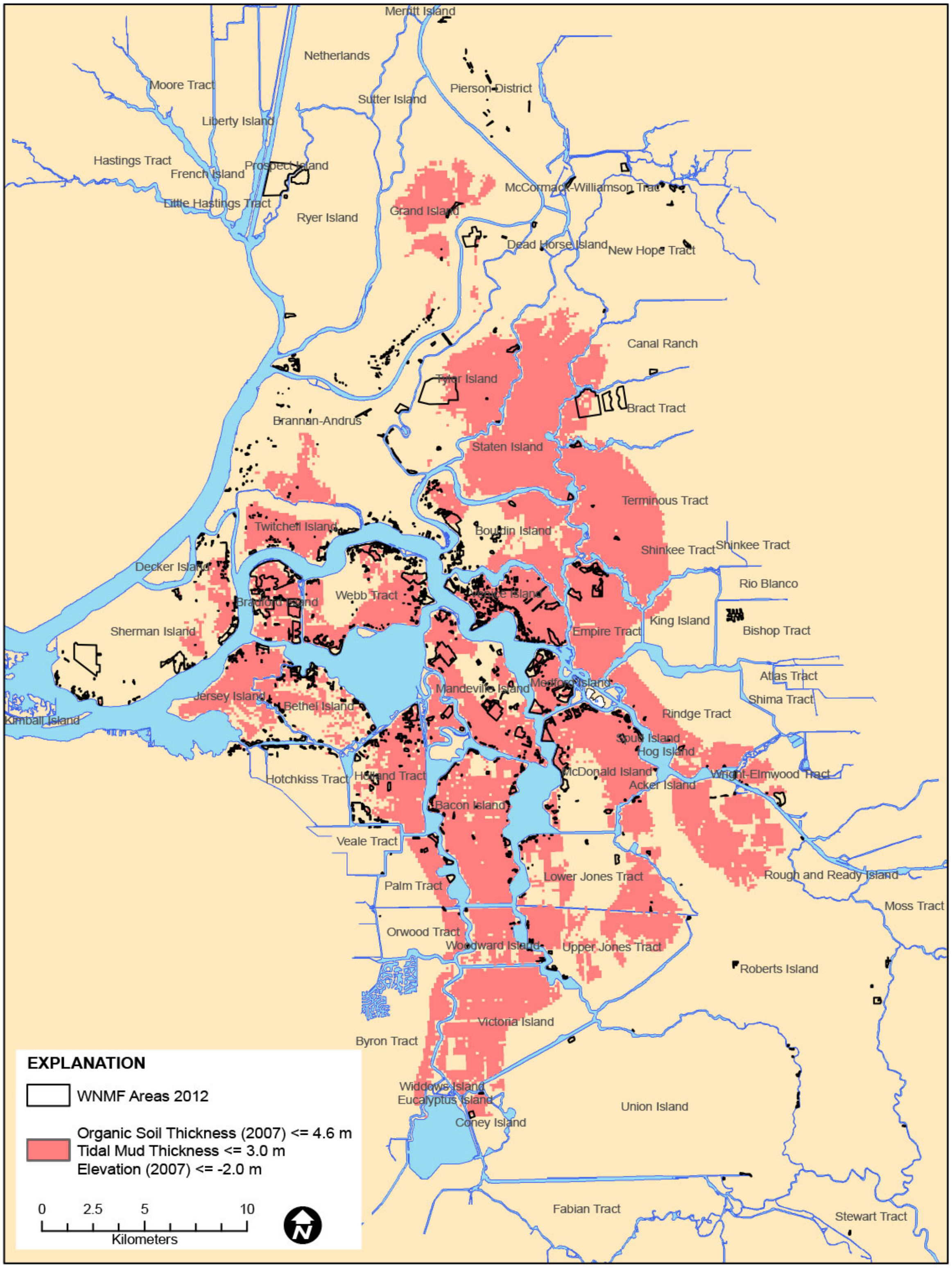


Figure 12 WNMF areas overlaid on the intersection of elevation at or below –2 m, organic soil thickness less than or equal to 4.6 m and tidal mud thickness less than or equal to 3 m.

Delta where there are organic soils, was 0.02 ha ha^{-1}. Also in the intersection area, 82% of the WNMF areas were within 1,000 m of the levee.

Groundwater Elevations

Groundwater hydraulics influence the evolution of WNMF areas. In light of the data shown in Appendix B, we deemed it reasonable to estimate average groundwater elevations for delineating artesian areas (Figure 13). Artesian conditions are defined by a groundwater elevation above the top of the aquifer. We defined the upper elevation of the aquifer that underlies the organic soil as the bottom elevation of the organic soils which we delineated using the methods described above.

Average groundwater elevations varied spatially from a maximum of 0.55 m on Hotchkiss Tract to a minimum of –4.8 m on Bacon Island and vary spatially independently of surface water elevations (Figure 13). Mean surface-water stage varied from 1.66 m in the northern Delta to 1.26 m in the western Delta (Figure 13).

The available groundwater level data indicate that artesian conditions prevail below land–surface elevation of about –2 m (Figure 13). In the western Delta, groundwater level data from wells in the Dutch Slough area show that artesian conditions prevail below elevations of –2.3 m. On Jersey, Sherman and Twitchell islands, artesian conditions prevail below –3 m. On Brannan–Andrus, Staten, and Woodward islands; and on Terminous, Lower Jones, Holland, and Palm tracts, artesian conditions prevail where elevations are less than –3 m. On Wright–Elmwood and Roberts, artesian conditions exist where elevations are –0.8 to –1.5 m. The large majority (82.6%) of the WNMF areas are within the 67,800 hectares delineated as artesian.

Artesian conditions result from hydraulic pressure transmitted from adjacent channels to the aquifer below the tidal deposits and thus result in upward movement of groundwater. Available data indicate that artesian conditions exist near levees and on the interior of islands. Specifically, all the wells screened below the organic deposits on Jersey Island show artesian conditions (Figure 13). Deverel et al. (2007a) reported similar conditions on Twitchell Island.

Land Management Practices

On Sherman and Twitchell islands, land-management practices have contributed to the observed WNMF areas, i.e., drainage ditches have not been regularly deepened. On Empire Tract, Palm Tract, Mandeville Island, Bacon Island, Bradford Island, Emerson Parcel, and Holland Tract, a substantial portion of organic soils have disappeared or the elevation of the organic-soil bottom is close to the bottom of drainage ditches. Excavation of drainage ditches into sandy materials that underlie the organic soils can result in drainage-ditch instability, and an inability to adequately drain the land for agricultural production. One long-time farmer described this phenomenon on the Emerson Parcel in the Dutch Slough area and on the southeastern part of Bradford Island where he farmed in the 1970s and 1980s.

Evolution of WNMF Areas

The time-dependent development of individual WNMF areas was difficult to discern because of sparse aerial photo and land-use time series. Many of the WNMF areas became evident in 2002 aerial photos and there were no available photos between 1993 and 2002. We were able to define the temporal changes in WNMF areas on Bacon and Bouldin islands (Figure 14). The areas on Bacon and Bouldin represent islands where drainage ditches have been generally well maintained. In the areas where WNMF areas have developed on Sherman and Emerson, drainage ditches have generally not been well maintained.

The WNMF area on Bacon Island (Figure 14A) expanded away from the levee from about 0.02 ha in April 2010 to 2 ha in August 2012. On Bouldin Island, the WNMF area grew from about 1 ha in 1993 to 52 ha in 2012. The rate of increase in the size of the WNMF areas on both of these islands slowed in recent years. The rates of increase in WNMF areas on Emerson and Sherman islands have not slowed in recent years (Figure 15). On Emerson, the WNMF

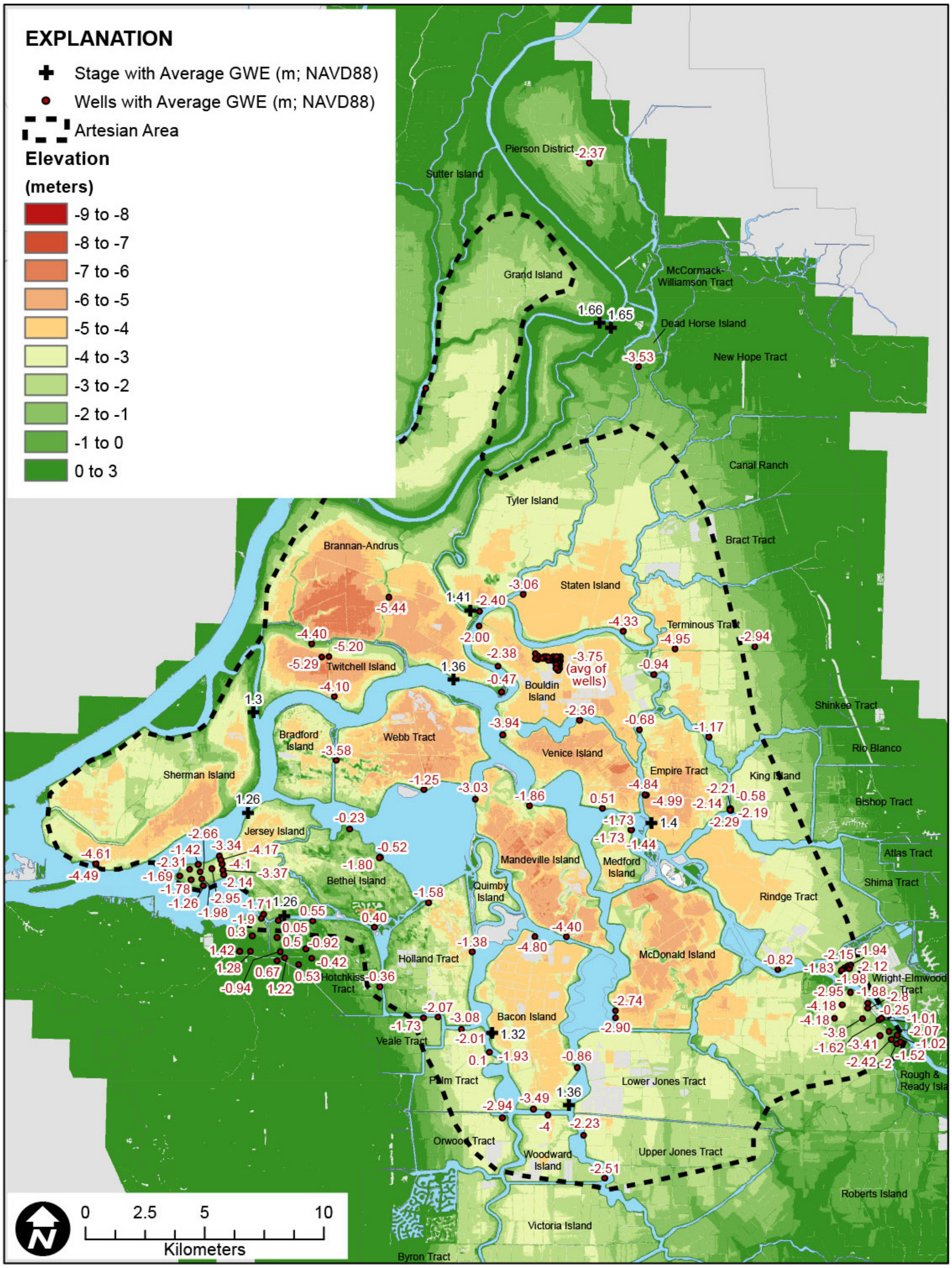
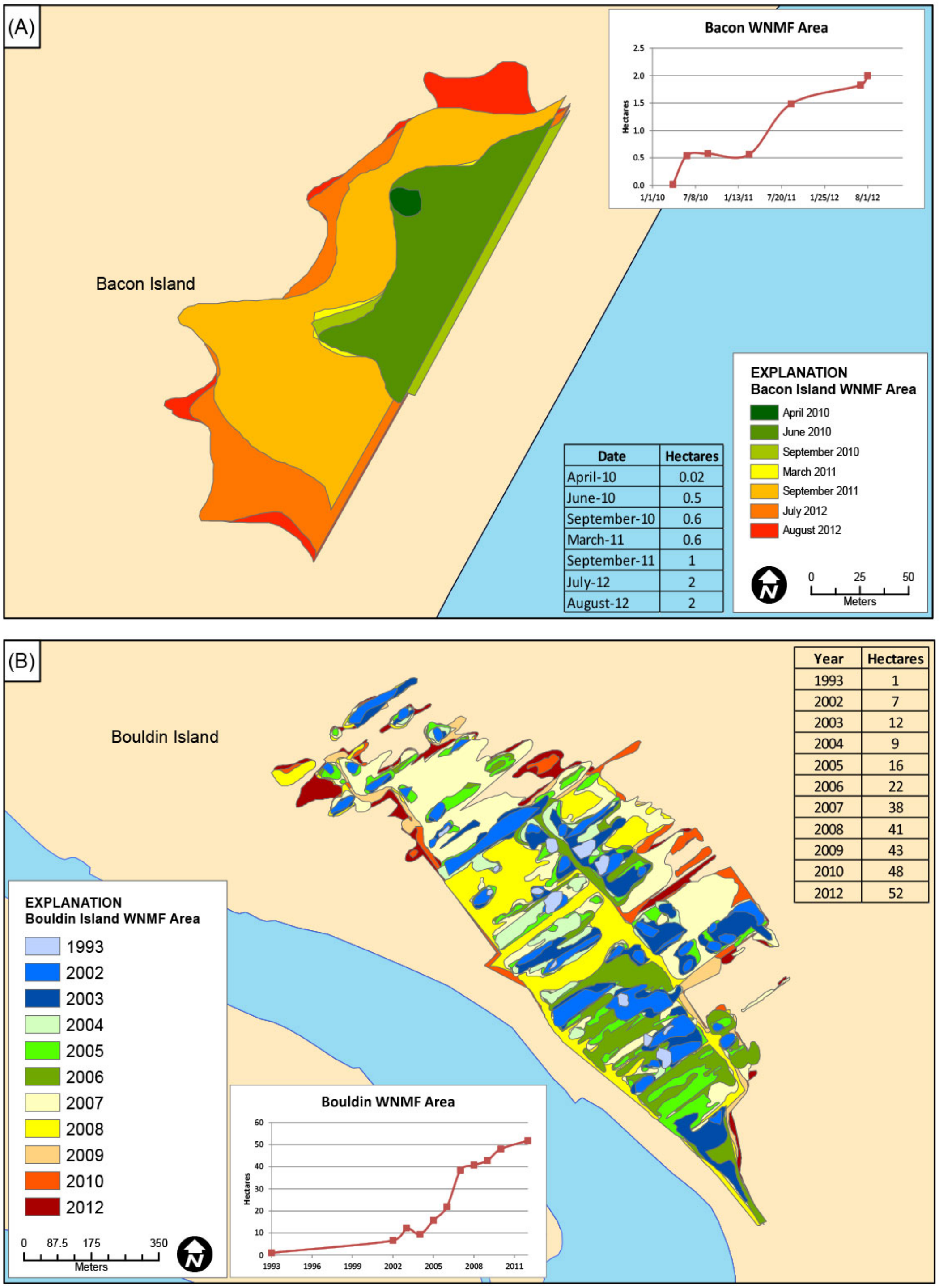


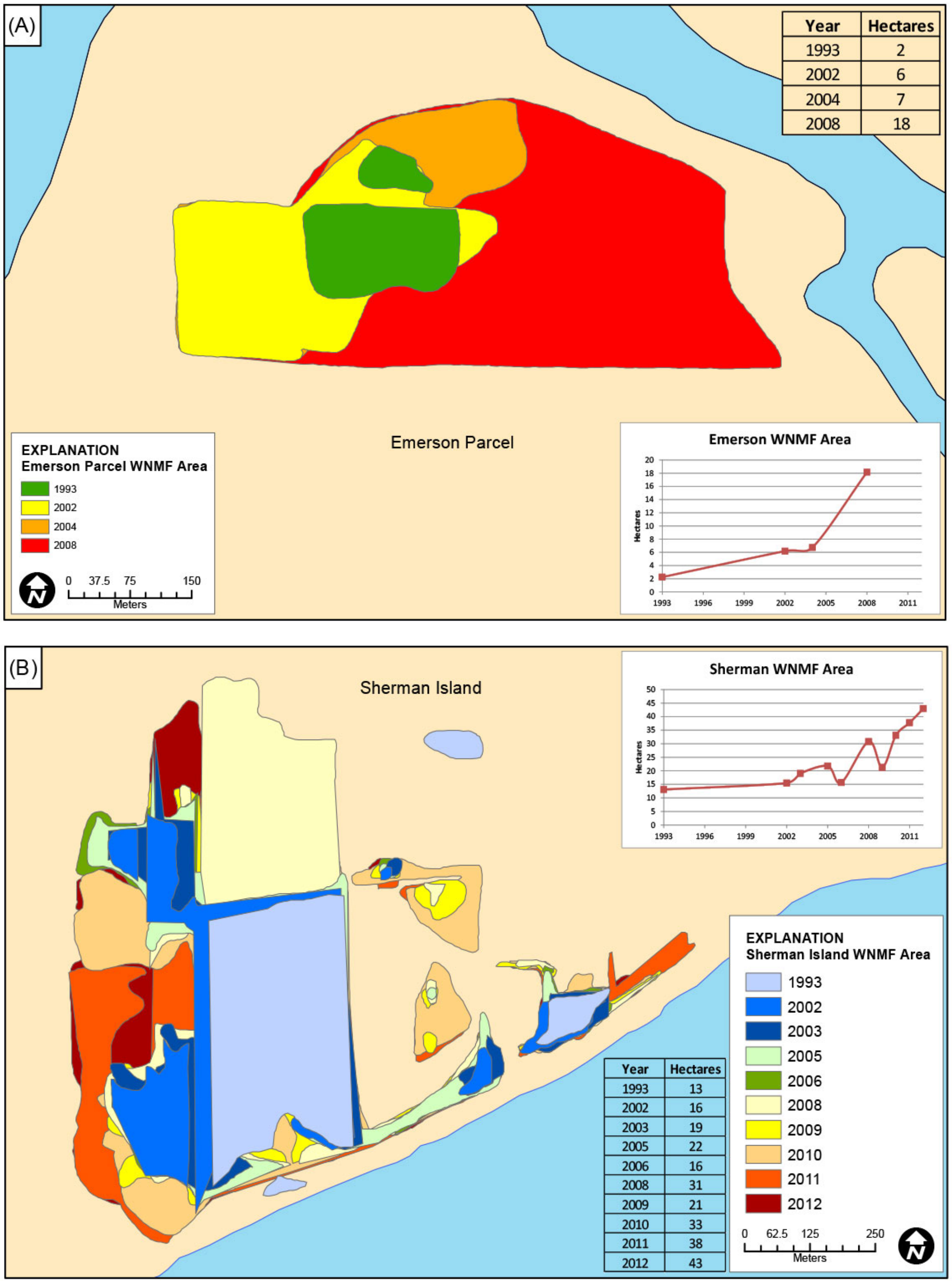
Figure 13 2007 Land–surface elevations, average groundwater elevations (1989–2012), average surface water stage elevations (2008–2011), and approximate area where there are artesian conditions



Date	Hectares
April-10	0.02
June-10	0.5
September-10	0.6
March-11	0.6
September-11	1
July-12	2
August-12	2

Year	Hectares
1993	1
2002	7
2003	12
2004	9
2005	16
2006	22
2007	38
2008	41
2009	43
2010	48
2012	52

Figure 14 Change in WNMF areas with time on **(A)** Bacon Island and **(B)** Bouldin Island



(A)

Year	Hectares
1993	2
2002	6
2004	7
2008	18

(B)

Year	Hectares
1993	13
2002	16
2003	19
2005	22
2006	16
2008	31
2009	21
2010	33
2011	38
2012	43

Figure 15 Change in WNMF areas with time on **(A)** Emerson Parcel and **(B)** Sherman Island

area grew from about 2 ha in 1993 to 18 ha in 2012 (Figure 15A). On Sherman, the WNMF area grew from about 13 ha in 1993 to 43 ha in 2012 (Figure 15B).

Future Reduced Arability

We surmised that subsidence and sea level rise will be the primary factors that contribute to future reduced arability. Subsidence will reduce the organic soil thickness which currently limits seepage onto islands. Also, hydraulic gradients onto islands will increase because of increasing sea level and decreasing land surface elevations.

Changing Land–Surface Elevation and Organic-Soil Thickness

We used SUBCALC (Deverel and Leighton 2010) and GIS to estimate organic soil thickness and land–surface elevation changes between 2007 and 2050. Land–surface elevation will decrease several cm to over 1 m by 2050. Less than 1-m decrease in elevation will occur around the periphery in the western, northern, and southern Delta. Less subsidence will occur in some areas of the western Delta, such as Sherman Island, because of low soil organic matter content and maintenance of a shallow water table in grazing areas. In the central Delta, we predicted that areas of Webb, Venice, Bouldin, Bacon, Woodward, Medford, Staten, and Tyler will subside 0.9 to 1.2 m by 2050. Subsidence will result in organic soil thinning. Figure 16 shows the estimated area underlain by 4.6 m of organic soil or less, and 3 m of tidal mud, and where land–surface elevations are less than or equal to –2 m in 2050.

Figure 17 shows the predicted potential WNMF area in 2050. We estimated that an additional 3,460 ha (8,540 ac) will be vulnerable to the development of WNMF conditions (blue areas in Figure 17). This is an increase of 24% relative to 2012, and would result in a total area of about 6,200 ha. Using the regression equation shown in Figure 6, we estimated that 6,250 ha will be WNMF by 2050. To delineate future area most susceptible to WNMF conditions, we assumed that within the green area of Figure 17 (estimated area underlaid by 4.6 m of organic soil or less, and 3 m of mud, and where land–surface elevations are less than or equal to –2 m in 2050), areas within 1,000 m of the levee will be the most vulnerable (blue areas in Figure 17).

Figure 17 shows that the area where WNMF conditions are likely to occur by 2050 will expand outwards to the west, north and east and southeast from the primary and centralized 2012 area. Specifically, we predict that under business as usual, WNMF areas will expand in the west on Brannan–Andrus, Sherman, Twitchell and Jersey. We predict that additional WNMF areas will appear on Webb, Mandeville, Bacon, Holland, Woodward, Lower and Upper Jones, Roberts, and Victoria in the central, southern and southeastern Delta. Moreover, we expect that additional WNMF areas will appear on Venice, Terminous, Staten, Tyler, and Grand in the eastern and northern Delta (Figure 17).

Hydraulic Gradients

We estimated that average Delta channel stage will rise by about 0.3 m by 2050. This, coupled with subsidence, will increase seepage onto islands and under-seepage exit gradients in drainage ditches adjacent to levees. Effects on island groundwater levels underneath organic soils and exit gradients depend on the head loss from the channel to the aquifer that underlies the organic soil. Using the Twitchell Island groundwater flow model (Deverel et al. 2007b), we estimated that the groundwater level change associated solely with projected sea level rise will be about 0.06 m by 2050. Therefore, the majority of the effect on seepage onto islands will likely be the result of thinning of organic soils and compensatory drainage-ditch deepening.

For example, on Bacon Island near the WNMF area shown in Figure 14A, the drainage ditch is about 2 m deep, resulting in a drain bottom elevation of about –3.5 m. Using the average groundwater elevation of –1.09 m from the nearby well screened below the organic soil (Figure 13) and about 60 cm of water in the drainage ditch, the estimated exit gradient equals 0.91. Deepening the drainage ditch to compensate for future subsidence of about 0.5 m by 2050 (Deverel and Leighton 2010) would result in an exit

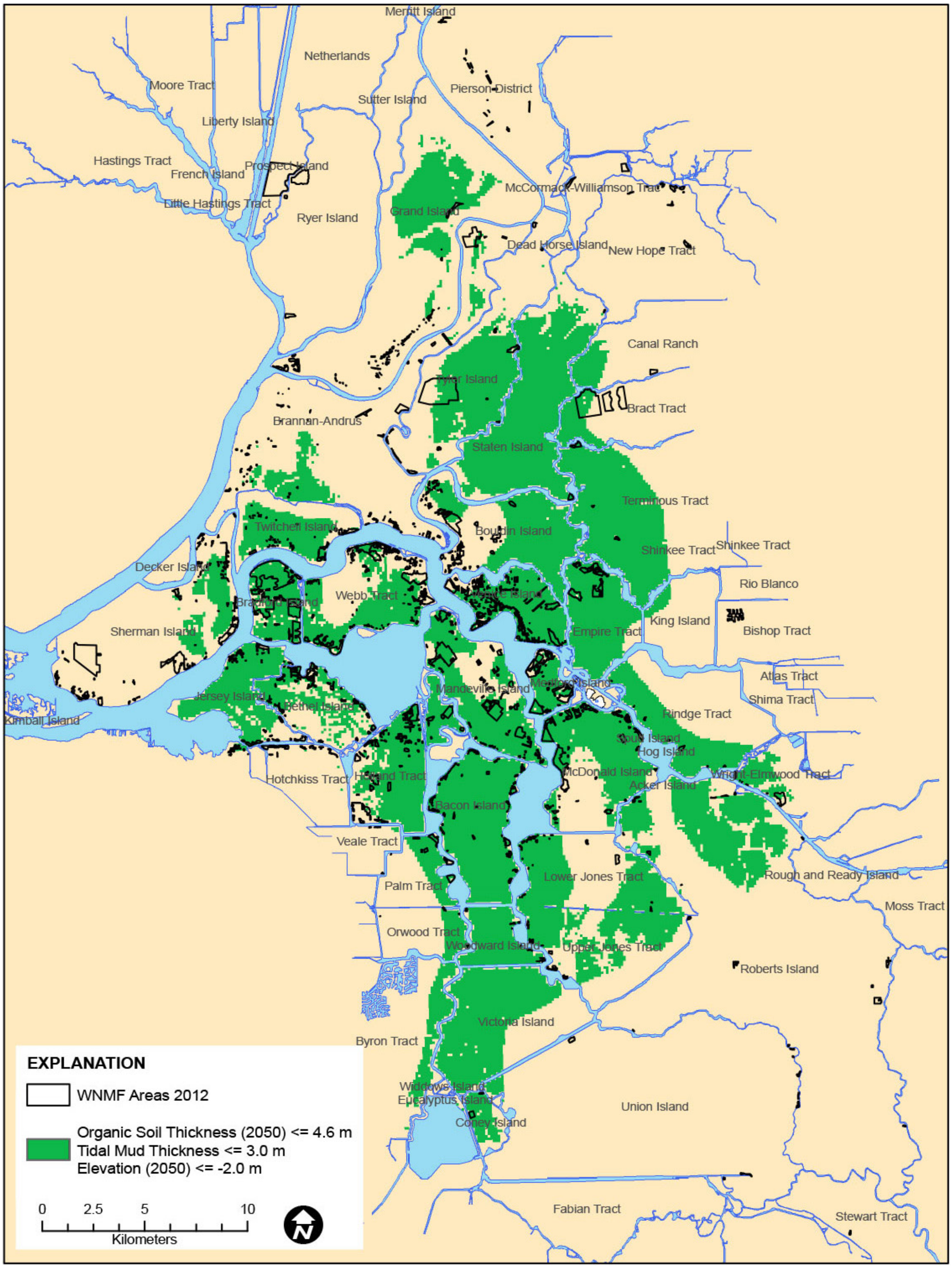


Figure 16 Estimated area underlain by 4.6 m or less of organic soil, 3 m or less of tidal mud, and where land–surface elevations are less than or equal to –2 m in 2050

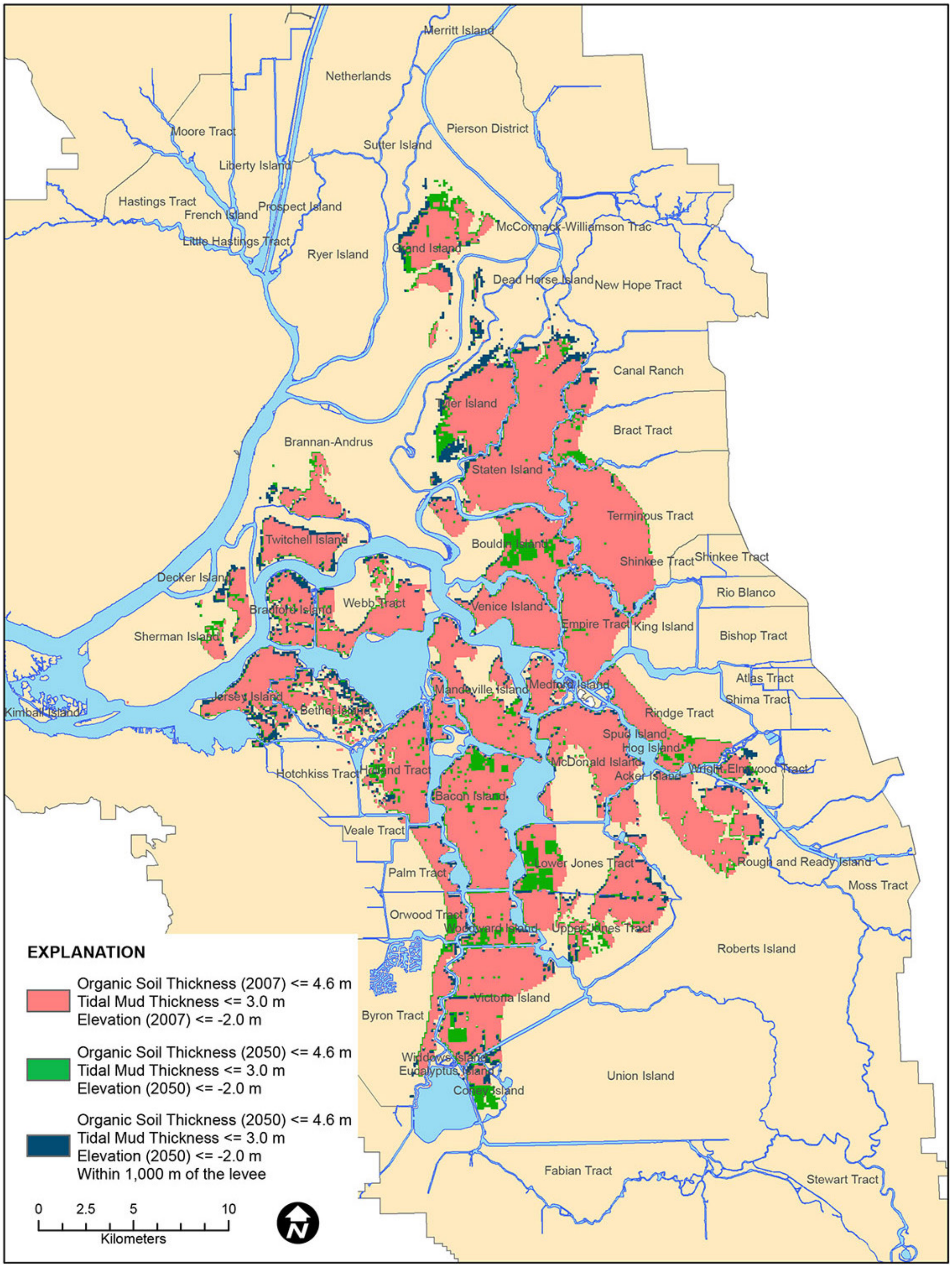


Figure 17 Increase in estimated area underlain by 4.6 m or less of organic soil, 3 m or less of tidal mud, where land–surface elevations are less than or equal to –2 m, and within 1,000 m of the levee

gradient of 1.3. Increasing the groundwater elevation by 0.12 m as the result of sea level rise would increase the exit gradient to 1.4. Similarly, on Upper Jones Tract near where Steven Deverel observed a sand boil in June 2012 in the toe ditch (after completion of levee upgrades), using data from the nearby observation well (Figure 13), we estimated the exit gradient to be 1.1. Projected subsidence of 0.5 m will result in an exit gradient of 2.0. With projected sea level rise resulting in an increased groundwater elevation of 0.06 m, we estimated a future exit gradient of about 2.1.

Groundwater Flow Model Results

We simulated groundwater flow paths from the levee to toe drains on Twitchell Island by placing particles into the toe drain in the same location in both 1910 and 2003 Twitchell groundwater models. The 1910 scenario shows that water travels directly from the levee to the toe drain, whereas the 2003 scenario shows water flowing from the levee down into the mineral layers before it heads up and discharges into the toe drain. Simulated seepage onto the island in the 2003 model was 11,073 $m^3\ d^{-1}$, over 15 times the simulated seepage in the 1910 model of 698 $m^3\ d^{-1}$.

DISCUSSION

We demonstrated an increase in total WNMF area and land use changes in the Delta from the 1970s and 1980s to 2012. Since 1984, WNMF areas have increased about 10-fold (Figures 1–6). Areas formally farmed for grain and hay are now used for grazing which requires less drainage and mapped areas of native vegetation have increased. Key factors associated with diminished arability and changing agricultural land use include diminishing organic-soil thickness, increased seepage under levees, reduced drainage management, and ability to drain. Our conceptual model for the increasing appearance of WNMF areas and changing land use relates decreasing elevations and diminishing organic soil thickness to changing seepage patterns.

Causes and Effects of Increased Seepage

Consistent with groundwater flow modeling results for Twitchell Island, Figure 18A shows a generalized geologic levee cross-section, and groundwater flow paths from the channel onto a central Delta island in the early 1900s based on levee dimensional information reported in Thompson (1957). Figure 18A also shows groundwater flow paths that we inferred based on the relative hydraulic conductivity of subsurface materials and groundwater levels. Note that the three shallowest layers for the Twitchell model correspond to the organic layer in Figure 18. Twitchell model Layers 4 and 5 correspond to the silt and underlying silty sand and sand layers.

Consistent with model results, flow to the toe drain occurred almost exclusively through the levee materials and underlying organic soil. Figure 18B represents present-day WNMF conditions where the thickness of organic soils decreased relative to the early 1900s. Figure 18B also shows the groundwater flow paths that we inferred based on an approximated flow net that uses the relative hydraulic conductivity of subsurface materials and groundwater levels. Similar to the Twitchell model results and in contrast to the early 1900s, substantial present-day flow to the toe drain occurs through mineral sediments that underlie the organic soils, and the hydraulic gradient is upwards from the deeper mineral deposits into the organic soil.

The aquifer that underlies organic soils consists of a downward coarsening sequence of sediments of primarily Sierran origin deposited during the Quaternary and Holocene that typically transitions from shallow silt and clay (mud) to silty sands to fine, medium and coarse sands. In many areas, muds are thin or absent. Groundwater moves upward from the underlying relatively highly conductive mineral sediments into the relatively low conductivity tidal muds and organic soils, toe drains, and other island drains further inland (Figure 18B). As organic soils disappeared, seepage increased onto islands, and the remaining organic soils became increasingly influenced by the groundwater pressures and higher flow in the underlying mineral aquifer. This increasing influence translates to more seepage and water flowing to drainage

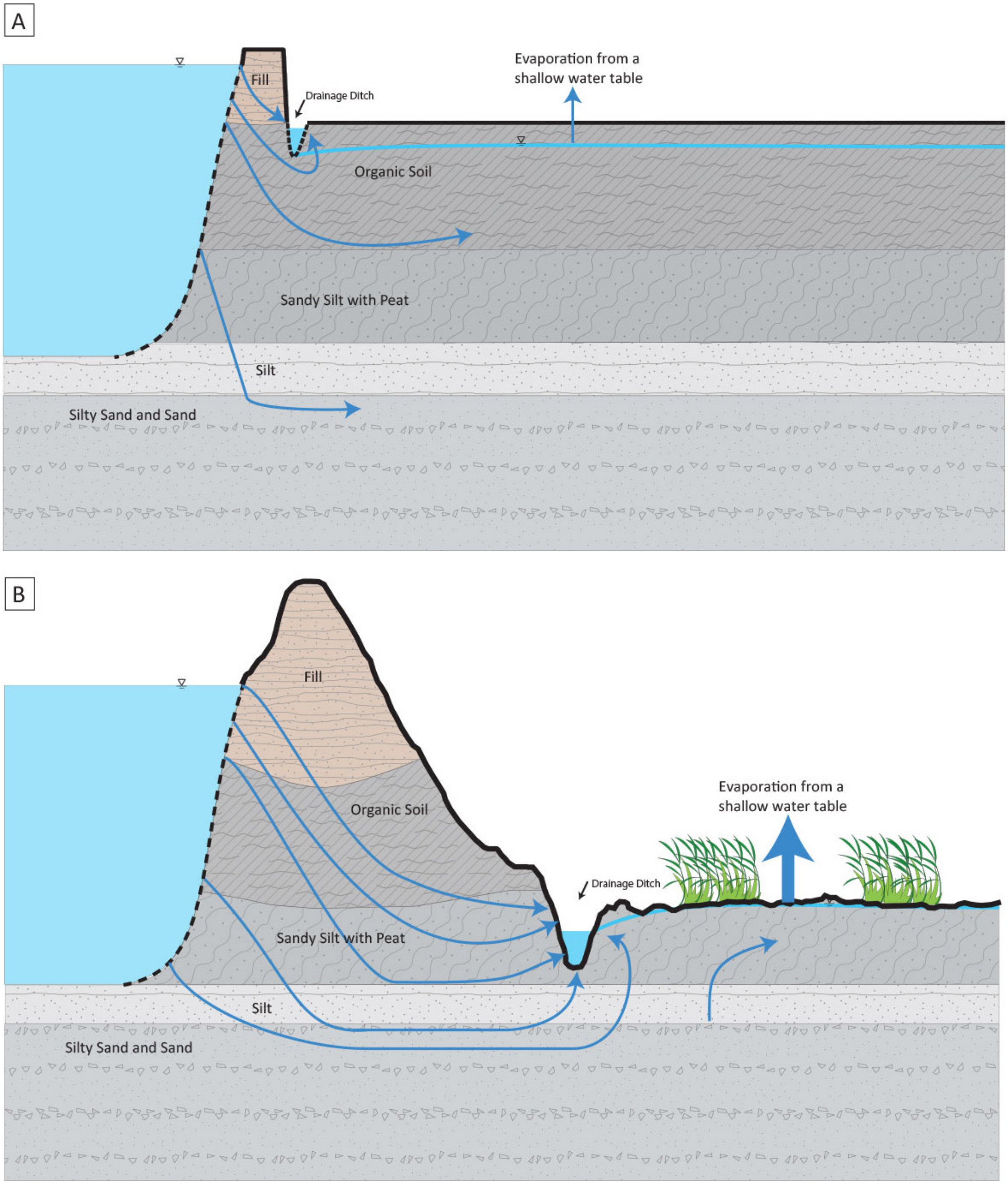


Figure 18 Levee cross section and conceptual model for **(A)** early 1900s conditions and **(B)** present day wet conditions

ditches and in the organic soils and, in some cases, hydraulic forces sufficient to move sands and silty sands to drainage ditches to cause sand boils. WNMF areas were probably caused by increased under-seepage from thinning organic soils and thin tidal mud, which is exacerbated in areas where land is close to the levee or surrounded on three sides by water.

Because of the low hydraulic conductivity, excess water moving into the organic soil is apparently not transmitted effectively to the drainage ditches and a WNMF area results. Because of the shallow water table in the organic soil, more groundwater evaporates relative to the better drained condition with a deeper groundwater level. For example, Gardner and Fireman (1958) demonstrated the dramatic increase in evaporation from the shallow water table when the depth to groundwater decreases. These authors showed that as the depth of the groundwater rose nearer to land surface, groundwater evaporation rates were two to over six times greater than when the groundwater table was lower than 1.5 m.

As the organic soil disappears, land–surface elevation decreases, and the shallow groundwater elevation must also be kept lower by deepening drainage ditches to allow for agricultural production. The increase in head difference between adjacent channels and island groundwater causes water to move into the organic soil at greater rates. Low organic hydraulic conductivity can prevent effective groundwater transfer to drainage ditches, and more water evaporates relative to the better drained condition. Evaporation becomes a larger sink for water entering the organic soil. Thus, two water-budget factors contribute to increased wetness and less ability to farm: More water enters the organic soil from below and results in a shallower water table, and shallower groundwater evaporates preventing effective drainage. Consistently, one farm manager stated that once areas become wet, they are difficult to drain by excavating additional drainage ditches.

Processes or Infrastructure for Reducing Growth of WNMF Areas

The process of increasing wetness can be self-limiting in that the higher water table limits further organic soil loss and increasing hydraulic gradients. Increased evaporation may also limit the development of additional wet areas by providing an evaporative sink for under-seepage. The growth of the size of the WNMF areas on Bacon and Bouldin islands illustrated in Figure 14 tends to confirm this, in that rates of WNMF-area growth slowed with time.

In some WNMF areas, drainage ditches at the toes of levees have been filled and replaced by ditches excavated farther landward. This may be accompanied by an extension of the levee landward. Mineral soils that cover the organic soil reduce or stop oxidative subsidence. This reduces the exit gradient because the hydraulic head in the mineral aquifer decreases with increasing distance from the channel (Deverel et al. 2007a). Also, the organic-soil typically thickens inland (Deverel et al. 2007a; Deverel and Leighton, 2010). However, as subsidence removes the organic soil adjacent to the new ditch and the ditches are subsequently deepened, the exit gradient will increase. Therefore, excavating new ditches further inland is a temporary solution in areas prone to seepage.

Buried perforated drainage pipe has been used in some locations. The farmer on Grand Island reported the use of this drainage technique to ameliorate seepage problems. However, reduced (ferrous) iron in groundwater can oxidize to ferric iron and precipitate upon exposure to oxygen and clog the perforations in buried drainage pipe. For example, on Ryer Island, subsurface drainage pipe reportedly clogged with iron oxides within 6 months after installation (2013 phone conversation with Glenn Drown, LIDCO, with Steven Deverel, unreferenced, see “Notes”).

Mud Thickness and WNMF Areas

Spatially variable mud thickness influences the development of WNMF areas (Figure 9). The thickest mud and organic-soil deposits occur on Sherman Island where tidal waters first inundated the Delta as sea level rose (Shlemon and Begg 1975; Atwater 1980) (Figures 8 and 9). Tidal deposition and organic-soil formation subsequently expanded north and eastward (Shlemon and Begg 1975; Deverel and Leighton 2010). Mud deposits formed in areas easily inundated by tidal waters as well as in relatively flat and low-

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lying areas and in tributary flood plains where lower stream velocities and a laminar environment resulted in the settling out of silts and clays as tidal mud deposits.

Two primary geomorphic processes interacted with tidal marsh formation to result in the observed distribution and thickness of the tidally-deposited muds. Fluvial deposition resulted in the formation of stream channels, floodplain deposits, and alluvial fans. Wind-blown alluvial deposits underlie organic soils in the southwestern Delta. As organic soils have disappeared, these sand dunes have been exposed. In the area of mapped eolian deposits, mud thickness is generally less than 1.5 m in areas where there are WNMF areas in the central-southwestern Delta (Atwater 1982) on Bethel, Holland, Bradford, Webb, Palm, Orwood and Hotchkiss. Dune sands trend southeastward, suggesting origins from the Sacramento and San Joaquin rivers and floodplain deposits that were transported inland before the most recent sea level rise into the Delta about 7,000 years ago (Atwater 1982).

Other WNMF areas shown in Figure 9 overlie relatively thin mud deposits such as Upper Jones Tract near the location of the 2004 levee break. During a June 2012 field visit to this location, organic soil was clearly visible near the ditch. The organic-soil thickness is mapped as 1.5 m or less (Figure 8). The toe drain was about 1.2 m deep, with less than 30 cm of water. Blue-gray and gray sands and silts were evident next to and in the ditch, and there was sloughing of these materials into the drainage ditch and upwelling of these materials in a sand boil. This sloughing is likely similar to the process described on Bradford Island where drainage ditches were difficult to maintain as the organic soil disappeared. Figure 9 shows that the mud thickness at this location was 3 m or less. The thinner mud deposits in this area are associated with the San Joaquin River and Old and Middle rivers (Figure 9), where relatively high-velocity fluvial deposition in these areas likely resulted in the thinner mud deposits. WNMF areas on Bacon Island that overlie thin (0 to 1.5 m) mud deposits also were likely influenced by these depositional processes.

WNMF areas on Mandeville, Venice, and Bouldin generally overlie or are adjacent to mapped mud thicknesses ranging from 1.5 to 3 m. These deposits are associated with the San Joaquin River and probably represent riverine and flood plain deposits. The WNMF and native vegetation area on Empire is associated with Mokolumne River deposition and mud thickness less than 1.5 m. WNMF areas that overlie mud thicknesses of 1.5 m or less on Twitchell and Sherman—and less than 3 m on Tyler and Grand islands—are associated with Sacramento River deposition. The general lack of WNMF areas on Brannan–Andrus Island is associated with thicker muds (3 to 5 m, up to 9 m in the south), which are probably Sacramento River flood plain deposits.

Future WNMF

In light of our conceptual model, thinning organic soils in the more deeply subsided central Delta where tidal muds are thinner are most susceptible to the development of WNMF conditions. Therefore, we attempted to map areas where WNMF areas are likely to occur in the future (Figures 16 and 17). We estimated an additional 3,460 ha where the organic soil thickness, land–surface elevation, and mud thickness create conditions conducive to forming WNMF areas by 2050. Subsidence mitigation measures include land conversion to permanently flooded wetlands and rice which have been shown to reverse the effects and stop or greatly reduce subsidence and seepage (e.g., Deverel et. al. 1998, 2014; Miller et al. 2000, 2008; Hatala et al. 2012).

The total WNMF area is relatively small compared to agricultural land in the entire legal Delta (about 215,000 ha), and is generally confined to the central Delta where there are subsiding organic soils. Therefore, the socio-economic effects of lost farmland from increasing WNMF areas appear to be small. However, the increasing WNMF area and our conceptual model indicate seepage will increase with decreasing organic soil thickness, which may have wider economic implications for levee stability. Strategic implementation of alternative land uses discussed above will reduce hydraulic gradients and seepage. Additional groundwater hydrologic analysis throughout the Delta will be helpful in estimating the extent of future effects.

SUMMARY AND CONCLUSIONS

We used available data to estimate changes in land use and wet, non-farmed or marginally farmed (WNMF) areas in the Delta from 1984 to 2012 and developed a conceptual model for processes that affect the observed changes. We analyzed aerial photography, groundwater levels, land–surface elevation data, well and boring logs and surface water elevations. We used estimates for sea level rise and future subsidence to assess the vulnerability of the land to the development of less arable areas. Key conclusions follow.

The cumulative WNMF area increased linearly about 10-fold, from about 274 ha in 1984 to about 2,800 ha in 2012. Moreover, several islands have experienced land use changes associated with increased wetness. These have occurred primarily in the western and central Delta, where organic soils have thinned, there are thin underlying mud deposits, and drainage ditches have not been maintained. On several islands, land formerly farmed to grains and field crops was recently mapped as pasture or native vegetation.

WNMF areas are generally associated with 4.6 m or less of organic soils, elevations less than about –2 m, tidal mud thickness less than 3 m, and areas within 1,000 m of levees. Subsidence is the key process that will contribute to increased likelihood of WNMF areas in the future. Subsidence will reduce the thickness of organic soils and increase hydraulic gradients onto the islands. To a lesser extent, sea level rise will also contribute to increased seepage onto islands by increasing groundwater levels in the aquifer under the organic soil and tidal mud, and by increasing the hydraulic gradient onto islands from adjacent channels.

Our conceptual model attributes the development of WNMF areas to increased seepage under levees, which was caused by changing flow paths as organic soil thickness decreased. The low hydraulic conductivity of the organic soil results in reduced ability to drain the land and greater evaporation losses. This process is exacerbated where there are thin tidal mud deposits. Based primarily on projected reduced organic soil thickness and land–surface elevations, we delineated an additional area of about 3,450 ha that is vulnerable to increased wetness and reduced arability by 2050. When added to the mapped 2012 WNMF areas, we estimated a total of 6,260 ha by 2050. The regression equation that relates WNMF area and time predicts 6,260 ha by 2050 or a 23-fold increase relative to 1984.

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