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RESEARCH

Evaluating the Aquatic Habitat Potential of Flooded Polders in The Sacramento–San Joaquin Delta

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ABSTRACT

Large tracts of land in the Sacramento–San Joaquin Delta are subsided because of agricultural practices, creating polders up to 10 m below sea level that are vulnerable to flooding. As protective dikes breach, these become shallow, open-water habitats that will not resemble any historical state. I investigated physical and biotic drivers of novel flooded polder habitat, using a Native Species Benefit Index (NSBI) to predict the nature of future Delta ecosystems. Results suggest that flooded polders in the north Delta will have the ecology and fish community composition of a tidal river plain, those in the Cache–Lindsey Complex (CLC) will have that of a tidal backwater, those in the confluence of the Sacramento and San Joaquin rivers a brackish estuary, and those in the south Delta a freshwater lake. Flooded east-side Delta polders will likely be a transitional zone between south Delta lake-like ecosystems and north Delta tidal river plains. I compared each regional zone with the limited available literature and data on local fish assemblies to find support for NSBI predictions. Because flood probabilities and repair prioritization analyses suggest that polders in the south Delta are most likely to flood and be abandoned, without extensive intervention, much of the Delta will become a freshwater lake ecosystem, dominated by alien species. Proactive management of flooded tracts will nearly always hedge risks, save money, and offer more functional habitats in the future; however, without proper immediate incentives, it will be difficult to encourage strong management practices.

KEY WORDS

Polder, flooded island, restoration, reconciliation ecology, novel ecosystems, Sacramento–San Joaquin Delta

INTRODUCTION

Twentieth-century land-use practices have accelerated land subsidence and polder formation around the globe, especially where land reclamation is combined with intensive agriculture near rivers and estuaries (McCreary et al. 1992; Lindenschmidt et al. 2009). Amid rising sea levels, there is growing concern about how or whether to manage these lands against flooding. Increasing pressure on levees will result in flooding and permanent land loss, but little is known about what will become of these flooded polders once they are inundated. These lands are highly altered from their original form, and will form novel aquatic habitats with largely unknown consequences for resident species.

In the Sacramento–San Joaquin Delta (Delta), islands were historically reclaimed from floodplain or emergent marsh habitat by building levees, dredging channels, and draining the land. Subsidence was accelerated by soil oxidation and compaction from agriculture, reducing elevation as much as eight m below sea level in some cases (Weir 1950; Mount and Twiss 2005). These polders are vulnerable to flooding when levees collapse because o poor building materials, age, floods, earthquakes, and sea level rise (Thompson 1957, p. 19; Suddeth et al. 2010; Suddeth 2011). The area potentially affected by flooding in the Delta is substantial: approximately 140,000 hectares of land are at or above sea level, and the area of vulnerability will increase over the next several decades with sea level rise. Many polders have already flooded and been reclaimed over the past century. Several have been abandoned because it proved uneconomical to resuscitate them, or because they were targeted as environmental restoration projects. The largest of these include Franks Tract, Mildred Island, and Liberty Island (Logan 1990; Suddeth et al. 2010). The physical habitat conditions and biota of currently abandoned flooded polders in the Delta are varied, but the evolution from polder to flooded habitat is poorly understood, and has not been methodically studied. While there is considerable political will to restore parts of the Delta to support native fishes that are threatened or endangered (ICF International 2013), how flooded polders will support or work against these goals is poorly understood.

To address this gap in understanding, I developed a Native Species Benefit Index (NSBI) to evaluate flooded polder ecosystems using just elevation, hydrodynamic flow, and turbidity. I wanted to address the questions:

1. *How will these factors determine the development of novel aquatic habitat after polder flooding?*
2. *What regional differences can be expected from flooded polder habitat?*

METHODS

Site Description

The convergence of the Sacramento and San Joaquin rivers forms the tidal freshwater Delta, a network of braided channels separated from the sea by the brackish and salt water embayments of the San Francisco Estuary (estuary) (Conomos et al. 1985). The Delta consists of at least four distinct hydrodynamic provinces (Whipple et al. 2012): the south, north, and eastern Delta each have different freshwater sources, while the western Delta is influenced by brackish water from Suisun Bay. Flow patterns and timing, soil types, geomorphology, and riparian vegetation differ among the regions.

The Delta has been developed into a hub of agriculture and water transport since the 1850s. Intense usage caused Delta islands to be transformed into polders, which are protected from flooding by a network of peat and riprapped levees. The resulting inverted landscape is shown in Figure 1, where waterways are elevated at or above sea level, and adjacent farmed polders are well below; in this landscape, boaters look over the levee and downhill to see farmhouses and fields.

Subsidence has led to increasing pressure on dikes, which vary in construction and reliability (Thompson 1957), leading to regular dike failure and flooding (URS/JBA 2008; Suddeth et al. 2010). A number of tracts have been permanently abandoned in this way, including Sherman Lake, Big Break, Little Mandeville Island, Franks Tract, Mildred Island, and Liberty Island. Other polders, such as Prospect Island and McCormick–Williamson Tract (which failed and was reclaimed in 2017), have been acquired with the intent to flood as mitigation for Delta water export and associated entrainment and mortality of Delta Smelt and salmon. Decisions to repair are based upon land value, infrastructure, population density, and importance to water management (Suddeth et al. 2010; Suddeth 2011).

Ecological Characterization

Historically, the Delta was characterized by intertidal and emergent marsh habitat, connected by an extensive channel network (Whipple et al. 2012). Anthropogenic alteration, drought, and species

Figure 1 Poldered islands in the Sacramento-San Joaquin Delta, viewed as a digital elevation model overlain with satellite imagery and with vertical relief exaggerated 10x. Two large permanently flooded polders are shown on the left half of the image. The other tracts range from 3-8 meters below sea level. Irregularities in polder surfaces are due to orchard crops, dikes, and buildings (Image credit: Burak Yikilmaz).

invasions have created a novel ecosystem without historical precedent, dominated by open-water habitat, few wetlands, and a mix of native and invasive alien species (Moyle et al. 1986; Nichols et al. 1986). During the drought of 1987–94, a number of alien species were introduced to the Delta, and previously introduced species expanded their range. The alien clams *Potamocorbula amurensis* (Nichols et al. 1990; Kimmerer 2004; Winder and Jassby 2010; Winder et al. 2011) and *Corbicula fluminea* (Hymanson et al. 1994) spread throughout the Delta and Suisun Bay, causing chronic phytoplankton depletion. The submersed aquatic weed *Egeria densa* expanded its range, altering the structure and function of open-water tracts and slow-moving sloughs (Grimaldo and Hymanson 1999; Toft 2000; Brown 2003; Durand et al. 2016). By 2000, pelagic organisms had greatly declined in the upper estuary (Sommer et al. 2007). However, not all regions of the Delta have responded in the same way. Suisun Marsh has been largely unaffected by the pelagic organism decline (O'Rear and Moyle 2010; personal data 2007–2016). In addition, Suisun Marsh, the CLC, and Liberty Island have had much more limited invasions of submersed aquatic vegetation (SAV) and clams (personal observations 2007–2016; Baumsteiger et al. 2017).

Regional and local differences are likely to influence how polders develop into aquatic habitat. For example, when deeply subsided polders flood, tidally influenced lake-like environments are created. These are characterized by low-energy flood-dominated flows, high residence times, warm water, limited physical structure or structure provided by SAV, and mostly alien fishes dominated by the family *Centrarchidae* (Lucas et al. 2002; Nobriga et al. 2005; Young et al. 2011). When shallow polders flood, dynamic ebb-dominated flow patterns may create habitats with higher pelagic productivity, emergent intertidal or seasonal marsh, stands of SAV, and a diverse fish assembly that includes a mix of natives and aliens (Simenstad et al. 2000; Nobriga et al.

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2005; Nobriga and Feyrer 2007; McLain and Castillo 2010; Young et al. 2011), providing a more desirable outcome.

Given the extent of subsided lands, it is important to understand the physical differences among potentially flooded habitats to predict future environmental outcomes in the Delta. These are linked to a number of biological outcomes, including phytoplankton production, emergent vegetation growth, harmful algal bloom formation, alien aquatic vegetation growth, zooplankton production, and dispersal and pelagic fish suitability. The key physical drivers of elevation, hydrodynamic flow, and turbidity are likely to have outsized effect on the biological outcome of flooding polders and are discussed below.

Gradients of elevation can create habitat complexity that may accommodate a variety of aquatic species. At intertidal or shallow water elevations, tidal energy can interact with physical features to create a dynamic environment. Complex hypsometry can create refuges for fish and mixed residence times that promote pelagic food production. Shallow water can produce high concentrations of phytoplankton under certain conditions, supporting the pelagic food web. Shallow and intertidal elevations with emergent marsh vegetation may also support both pelagic and demersal food webs. In contrast, polders with elevations much below sea level may create open-water habitat that dissipates tidal energy and leaves little physical surface for tides to work against. Such habitat becomes more vulnerable to invasion by SAV like *E. densa*, which can change habitat dynamics. Unless deep open-water habitat stratifies, it is unlikely to promote phytoplankton blooms, in part because water circulates below the depth critical for photosynthesis (Simenstad et al. 1999, 2000; Lucas et al. 2002; Lopez et al. 2006; Ahearn et al. 2006; Thompson et al. 2008; Moyle et al. 2010; Whipple et al. 2012; Enright et al. 2013).

The timing and magnitude of hydrodynamic energy from tidal and riverine flows affect pelagic productivity, exchange of nutrients, and transport of food resources and pelagic organisms. Flow energy can discourage alien species that can alter the ecosystem, such as aquatic plants and sunfishes. Ebb-dominated flows help direct migratory and anadromous fishes on spawning migrations. Tidal energy creates mixed residence times along longitudinal gradients, which promote diversity and exchange of pelagic food web constituents and fish. In contrast, regions with low hydrodynamic energy create lake-like environments that tend to be dominated by alien fishes and aquatic plants, lack directional flows to support anadromous fishes, and have limited capacity to support and export pelagic food resources (Lucas et al. 1999a, 2002; Jones et al. 2008; Lehman et al. 2008, 2009; Fleenor et al. 2010; Durand 2015).

Turbidity provides cover for larval and juvenile native fishes, and adult Delta Smelt. Clear water makes fish more vulnerable to predation by visual predators. Smelt, larval, and juvenile fishes follow high-turbidity zones behaviorally, seeking refuge. Many native fishes are adapted to live under high-turbidity conditions by foraging on benthos. Invasive centrarchids, in contrast, are adapted to foraging in clear water on structural elements, such as wood or SAV (Grimaldo and Hymanson 1999; Toft et al. 2003; Feyrer and Healey 2003; Nobriga and Feyrer 2007; Ferrari et al. 2014).

Native Species Benefit Index

I used available data for depth, hydrodynamic flows, and turbidity to create a simple metric for polder evaluation. These factors allowed comparison of individual and regional differences among polders. Because most of the polders being evaluated are not flooded, elevation was the easiest metric to evaluate on an individual basis. Using a hydrodynamic model, I estimated potential hydrodynamic energy as flow from adjacent point locations in channels. I estimated turbidity using continuous monitoring data from multiple stations in adjacent to create regional estimates. Of course, each potentially flooded polder will have a unique geographic relationship to Delta hydrodynamics and climate, based upon location, structural morphology, number of breaches, and hydrodynamics. More explicit evaluation will require collection of data and modeling specific to each polder. The NSBI is a simple way to easily assess differences among 78 different Delta polders, all of which have some potential to breach and flood.

I evaluated diked reclamation districts in the Delta region that had areas within or below the intertidal zone (0–1.5 m above mean lower low water [MLLW]). I considered reclamation districts that had elevations greater than 1.5 m above MLLW to be above the intertidal range, and removed them from the analysis. Some of these, like Yolano and Peters Pocket, may provide amenable floodplain habitat if levees were removed. Peters Pocket, along with some other tracts, has a high probability of becoming intertidal with sea level rise. However, these "high-elevation" tracts were outside the scope of this study. I also removed reclamation districts west of the confluence of the San Joaquin and Sacramento rivers (the Confluence), and urbanized reclamation districts from the analysis. I used the following approaches to create metrics of depth, flow energy, and turbidity.

Depth

I used U.S. Geological Survey (USGS) topographic maps (USGS 2000), a digital elevation map from 2007–08 Light Detection and Ranging (LiDAR) data (Dudas 2010), and a continuous surface elevation map of the Delta (Wang and Ateljevich 2012) to determine elevation relative to MLLW (NAVD 88). Elevation and reclamation districts are shown in Figure 2. I used these data to assess the commonest elevations on each tract, and the upper and lower limits. I classified depths as follows: elevations more than 1.5 m below MLLW were subtidal deep water; elevations more than zero and less than 1.5 m below MLLW were subtidal shallow water; elevations greater than zero and less than 1.5 meters above MLLW were intertidal. I assigned each category points in proportion to the presumed benefits provided to desirable ecosystem processes. Polders received both primary and secondary points to represent the varied topography of each polder (Table 1). I gave primary depth points for the commonest elevation category. I gave secondary depth points for the categories crossed by the maximum and minimum elevations for each polder. I tallied points tallied for each tract and divided by six, the maximum points possible, which normalized scores to one.

Table 1 Elevation scores

Depth (m above MLLW)	Category	Primary points
< −1.5	Subtidal Deep	0
−1.5 — −0.1	Subtidal Shallow	1
0 — 1.5	Intertidal	3
Depth range (m above MLLW)		**Secondary points**
Range crosses < −1.5	Subtidal Deep	0
Range crosses −1.5 — −0.1	Subtidal Shallow	0.5
Range crosses 0 — 1.5	Intertidal	1.5
Range crosses >1.5	Emergent	1

Hydrodynamic Energy

I used estimated flow data from an RMA2 model (King 1988) for water years 1998, 2003, 2006, 2007, and 2008 at 20 different locations across the Delta (W. Fleenor, 2012 unpublished data, see "Notes"). Average daily flows (cfs) varied considerably among years with different hydrologic regimes (e.g., wet winters with high directional flows tend to create differences in riverine flow-dominated channels, while tidally-dominated channels remained relatively unaffected). I used Ward's Method to create correlations among sites that I plotted as a cluster dendogram (Figure 3). I then used clusters to plot daily flows as yearly time–series to confirm distinct patterns for geographic flow regions (e.g., Figure 4). Using amplitude of the plots, I assigned points to the resulting eight flow regions on a scale of 1 through 8, where 1 was for the lowest flow energy and 8 for the highest flow. I assigned polders to a flow region to receive a score, which was standardized to one (Table 2). Regions and scores are shown in Figure 5.

Turbidity

To evaluate turbidity, I extracted averaged daily turbidity estimates from 51 water quality stations deployed throughout the Delta for the time–period from 2006 through 2012. I downloaded data from the California Data Exchange Center (CDEC) website (*http://cdec.water.ca.gov/cgi-progs/queryCSV*, CDWR 2013). I plotted the time–series and found a high

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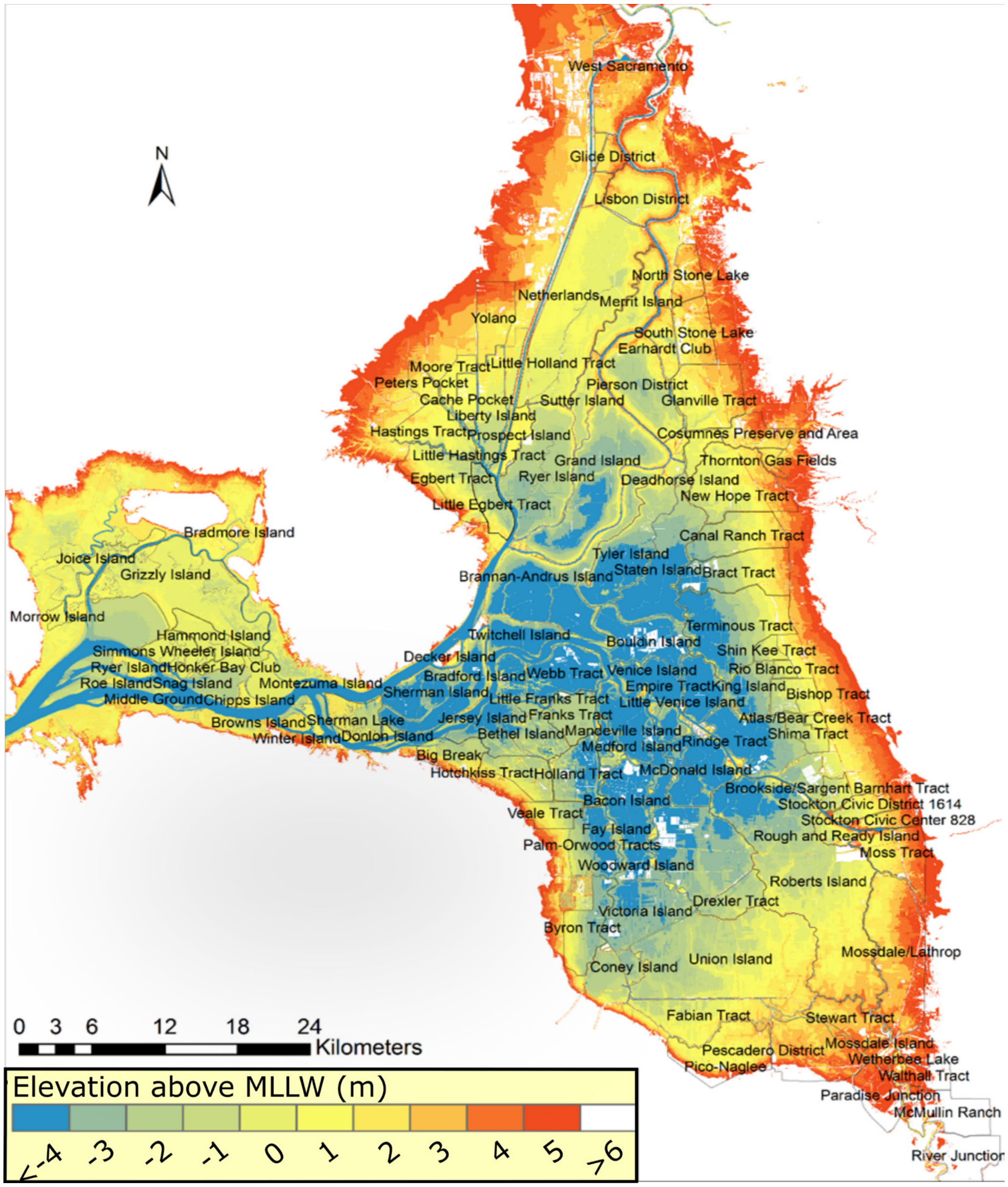

Figure 2 Delta polders and hypsometry (elevation in m above MLLW). White areas are artifacts of LIDAR survey data and post-processing, or elevations above 6 m.

degree of consistency in stations within regions (Figure 6). To create a regional index of relative turbidity, I took simple means of the daily average for each station from 2009 through 2012 (which included the most complete records) and mapped each station with its representative mean turbidity value (Figure 7). Using these stations as guides, I designated ten different geographic regions as having distinct patterns of turbidity. I scaled these regions according to Table 3, with 1 being the lowest-turbidity region and 5 being the highest. I then divided scores by five to standardize to one.

To calculate the NSBI score, I scored each polder from 0 to 3 by adding the three metrics (Table 4). The NSBI assumes no difference in relative benefits among the three factors. By weighting potential benefits equally, I provide a simple way to evaluate key conditions that drive different ecological outcomes, and ranked them as percentiles. I mapped the top and bottom 25% scores for the three

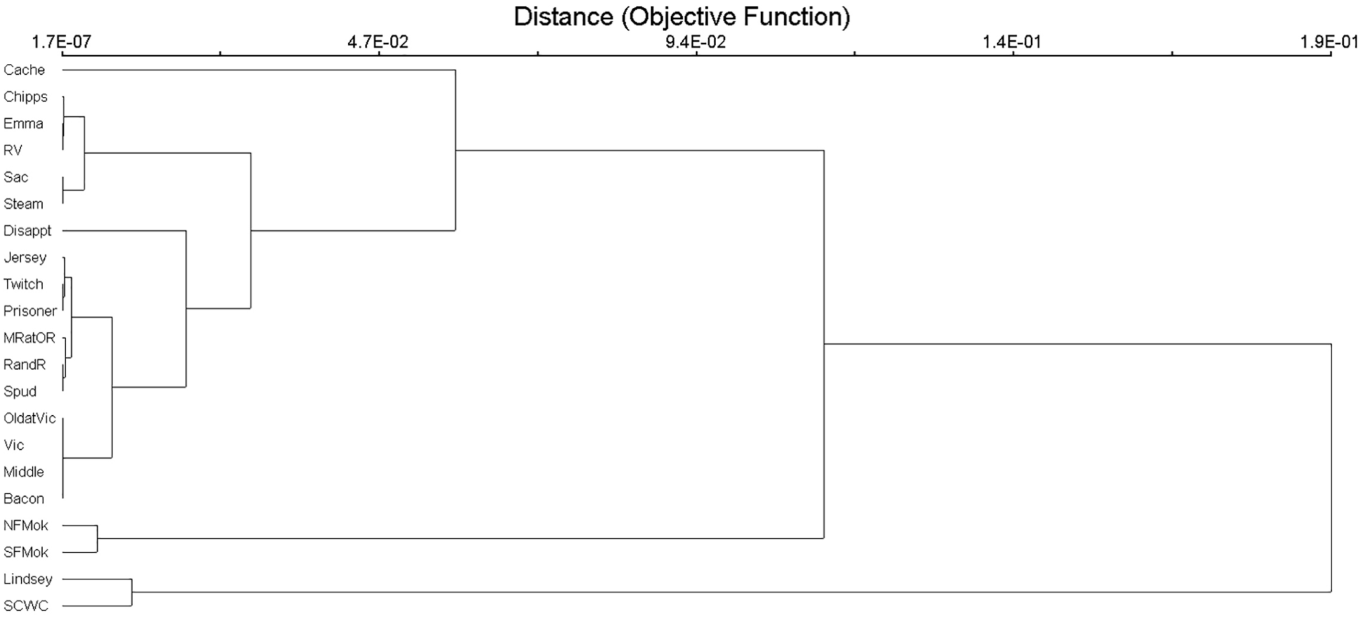

Figure 3 Cluster dendogram showing flow relationships among sloughs

Table 2 Flow regions, flow query sites, and scores

Region	**Sites**	**Abbreviation**	**Points**
South Delta	Old River at Bacon Island Lower Old River at Victoria Middle River Victoria Slough	Bacon OldatVic Middle Vic	0
Disappointment	Disappointment Slough	Disappt	1
Cache Complex	Cache Slough Lindsey Slough Sacramento Deep Water Ship Channel	Cache Lindsey SCWC	2
Suisun	Not included		3
East Side North	North Fork Mokelumne South Fork Mokelumne	NFMok SFMok	4
East Side South	Spud Island Rough and Ready Island Middle River at Old River	Spud RandR MRatOR	5
Sacramento–Steamboat	Steamboat Slough Sacramento River above Rio Vista	Steam Sac	6
SJR Central Delta	Jersey Point San Joaquin River at Twitchell Island Prisoners Point	Jersey Twitch Prisoner	7
Confluence	Chipps Island Emmaton Rio Vista	Chipps Emma RV	8

combined metrics to understand regional trends (Figures 8 and 9).

In addition to NSBI Score and Percent Rank for each polder, I tabulated Current Status, recommended Flood Response, Probability of Failure, and Reclamation District number (Table 4). Current Status indicated whether a polder is flooded, managed as a wetland, or non-flooded as of 2017. Flood Response gives the recommended action to be taken if levees fail and polders flood from Suddeth et al. (2010), and repair prioritization rankings from the Delta Risk Management Strategy (URS/JBA 2008) based upon the value of each polder to Delta operations and salinity control. Probability of Failure was also taken from Suddeth et al. (2010) and the Delta Risk Management Strategy (URS/JBA 2008). Colored highlights indicate geographic regions: red = Confluence, orange = north Delta, yellow = CLL Complex, green = east Delta, blue = south Delta, which were assigned to polders only in the top and bottom 25% ranks.

RESULTS

The highest-scoring polders came largely from the region of the Confluence, followed by polders from CLC and the north Delta (Figure 8). Polders in the

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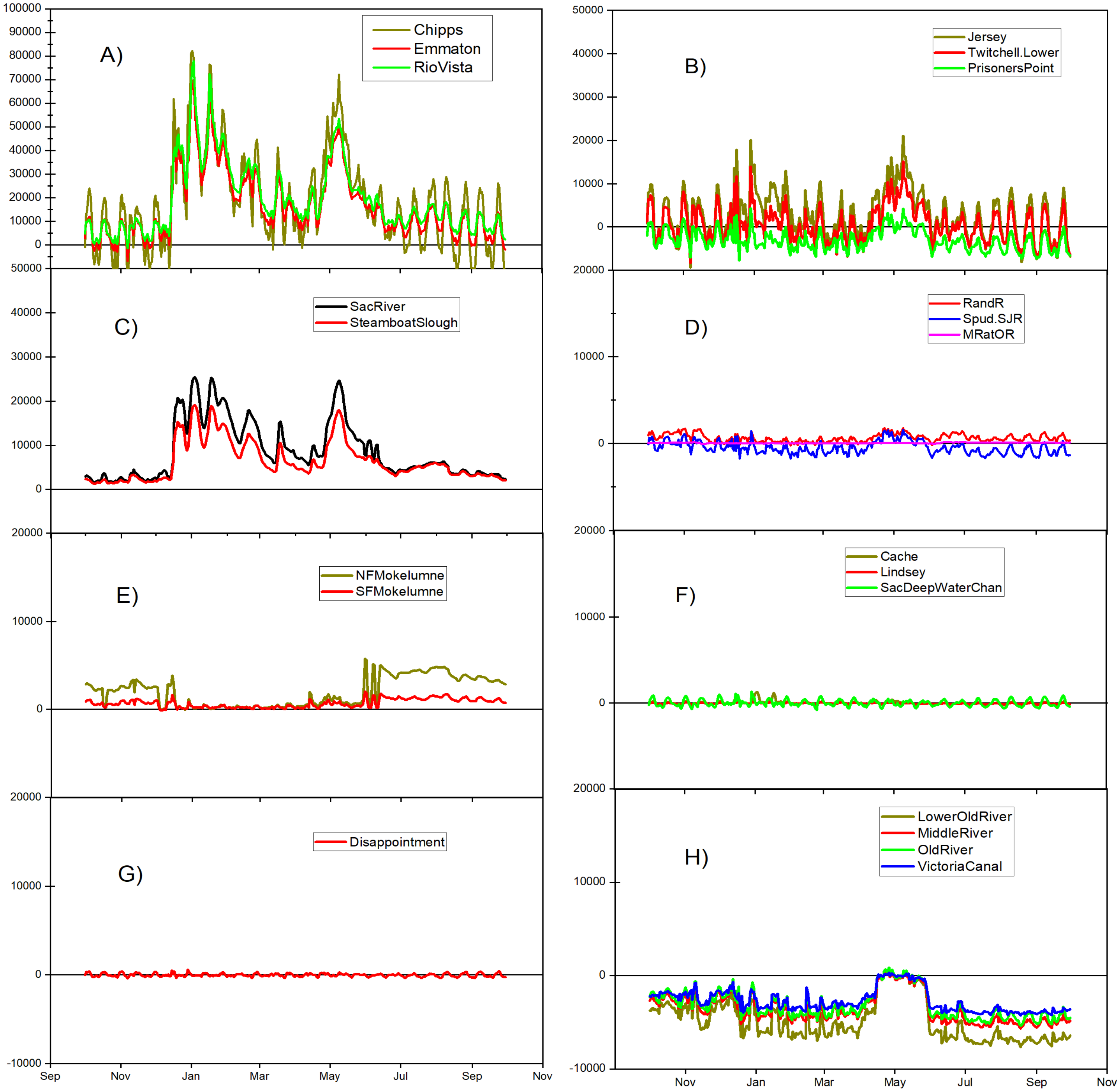

Figure 4 Modeled flows (cfs) at selected locations (shown in legend boxes) from a representative water year (October 1, 2002–September 30, 2003), clustered together by the following regions: **(A)** Confluence, **(B)** SJR Central Delta, **(C)** Sacramento/Steamboat, **(D)** East Side South, **(E)** East Side North, **(F)** Cache–Lindsey Complex, **(G)** Disappointment Slough, and **(H)** South Delta. Additional years were plotted separately with similar results.

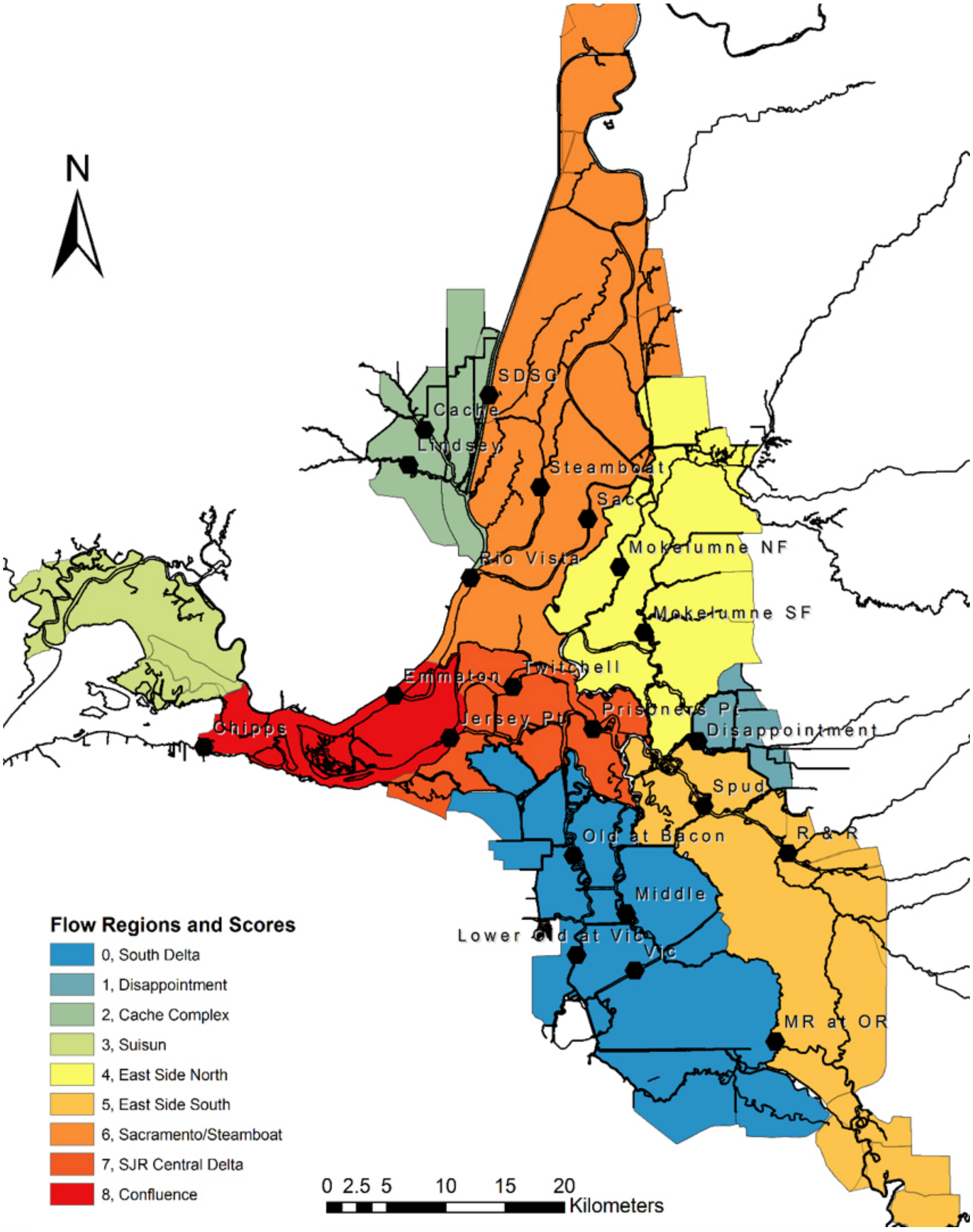

Figure 5 Flow regions by color. Corresponding points and names are in the legend. Sites where flows were modeled are indicated by black hexagons and named on the map. Note that tidal wetlands in Suisun Marsh were not evaluated in this study.

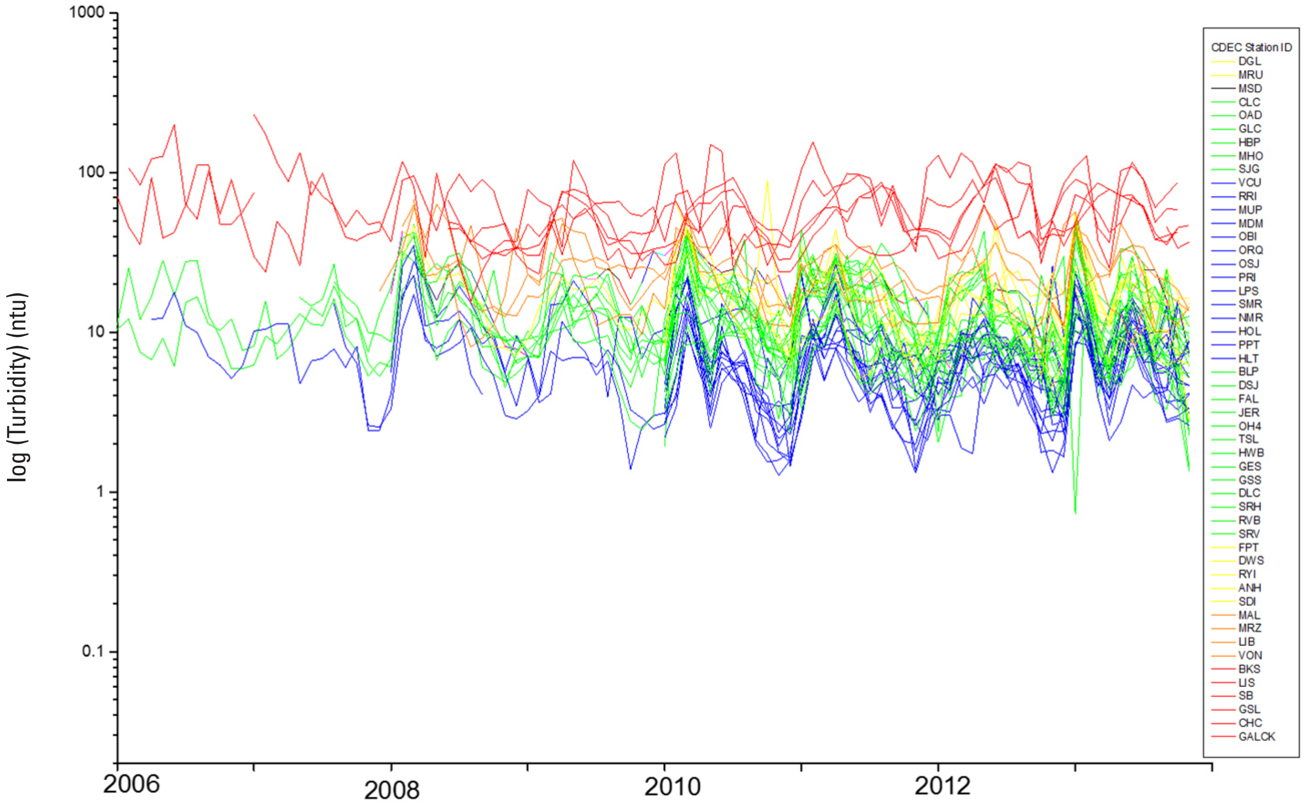

Figure 6 Turbidity (ntu) for 51 stations throughout the Delta from 2006-2012. Colors represent blocks of CDEC stations from similar geographic locations.

Table 3 Regional turbidity means and scores

Turbidity (ntu)	Points
5—9	1
10—14	2
15—19	3
20—29	4
30+	5

north Delta and the Confluence scored high because of their proximity to flows from the Sacramento River. The CLC has lower flow energy because it is mostly tidal, but received high scores for turbidity and shallow depth. Differences among these three regions can be summarized as a series of trade-offs among the three criteria that lead to differing ecological outcomes (Table 5). I classified habitat in the Confluence as Low Salinity Estuary, in the CLC region as Tidal Backwater, and in the north Delta as Tidal River Plain.

The lowest-scoring tracts came primarily from the east and south Delta (Figure 9). Nearly all of these tracts occur in the clearest water in the Delta. Most are subsided below sea level, deepening with proximity to the San Joaquin River corridor. The east-side polders have elevation gradients that are probably desirable for some wetland and subtidal restoration purposes, but they are limited by low flows and clear water. The south Delta polders have clear water, deep subsidence, and flows strongly affected by large south Delta water export pumping plants, giving these the lowest scores. I classified habitats in the east Delta region as a Transition Zone, and in the south Delta region as Freshwater Lake.

The tracts not in the top or bottom 25% of scores represent a range of conditions that overlap among regions. For example, although the polders adjacent to the San Joaquin River are generally the most subsided, many of these tracts did not score in

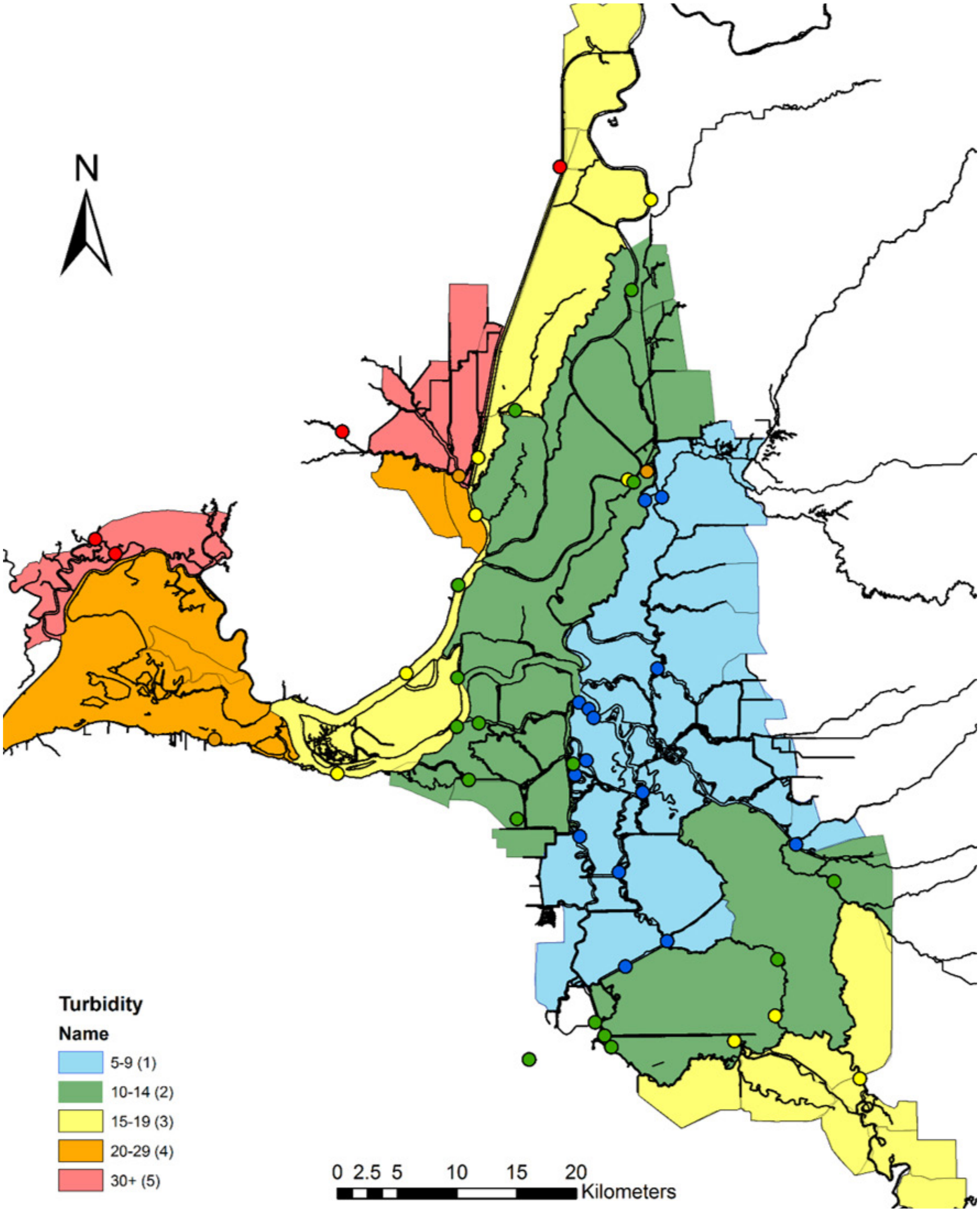

Figure 7 Turbidity regions in the Delta, averaged from CDEC values from 2009 through 2012

Table 4 Polders with NSBI score and percent rank. Current status is indicated by F = Flooded, F* = Intentional flooding planned; MW = Managed wetland; and intact if blank. Flood response gives the recommended response and priority of a number of polders: R = High value, repair if flooded; NR = Do not repair if flooded (Suddeth et al. 2010); U = Unsure. Numbers show repair priority where 1 = highest priority, and 69 is lowest (URS/JBA 2008). RD is reclamation district.

Polder	Score	Percent rank	Current status	Flood response	Probability of failure	RD
Sherman Lake	2.52	0.99	F	—	—	
Van Sickle Island	2.30	0.96	MW	?	0.07	RD 1607
Winter Island	2.30	0.96	MW	?		RD 2122
Netherlands	2.27	0.95		?	0.03	RD 999
Little Holland Tract	2.17	0.94	F	—	—	
Donlon Island	2.10	0.92	F	—	—	
Liberty Island	2.08	0.91	F	—	—	RD 2093
Libby McNeil District	2.07	0.89		?	0.01	RD 369
Merrit Island	2.07	0.89		?	0.01	RD 150
Hastings Tract	2.00	0.86		64	0.01	RD 2060
Moore Tract	2.00	0.86		?	0.03	RD 2098
Egbert Tract	1.97	0.85		63	0.01	RD 536
Rough and Ready Island	1.94	0.84		45	0.03	Stockton
Ehrheardt Club	1.90	0.82		—	0.01	RD 813
Lisbon District	1.89	0.81		—	0.03	RD 307
Little Egbert Tract	1.88	0.80		62	0.03	RD 2084
Prospect Island	1.85	0.78	F*	—	—	RD 1667
Grand Island	1.82	0.75		R/40	0.03	RD 3
Pierson District	1.82	0.75		42	0.01	RD 551
Sutter Island	1.82	0.75		41	0.01	RD 349
Cache Pocket	1.75	0.72	MW	?		
French Island	1.75	0.72		?		
Fern / Headreach / Tule islands	1.74	0.71	F	—	—	
New Hope Tract	1.70	0.70		54	0.07	RD 348
Roberts Island	1.69	0.68		R/23	0.05	RD 684/524/544
Sherman Island	1.68	0.67		R/38	0.07	RD 341
Little Venice	1.58	0.66	F	—	—	
Little Franks Tract	1.53	0.65	F	—	—	
McCormack–Williamson Tract	1.45	0.63	F*	—	0.03	RD 2110
Little Hastings Tract	1.42	0.62	F	—	—	
Big Break	1.40	0.59	F	—	—	
Veale Tract	1.40	0.59		18	0.01	RD 2065
Franks Tract	1.36	0.54	F	—	—	
Bradford Island	1.36	0.54		NR/36/36	0.09	RD 2059
Jersey Island	1.36	0.54		NR/37/37	0.01	RD 830
Webb Tract	1.36	0.54		NR/34/34	0.1	RD 2026
Twitchell Island	1.28	0.53		NR/35/35	0.05	RD 1601

Table 4 Polders with NSBI score and percent rank (Continued)

Polder	Score	Percent rank	Current status	Flood response	Probability of failure	RD
Ryer Island	1.23	0.52		R/61	0.03	RD 501
Brack Tract	1.20	0.51		R/65	0.05	RD 2033
Bishop Tract	1.16	0.49		67	0.01	RD 2042
Brannan-Andrus Island	1.15	0.47		R/33	0.05	RD 2067/317/407/556
Fabian Tract	1.15	0.47		10	0.01	RD 773
Mandeville Island	1.08	0.44		NR/26/26	0.05	RD 2027
Venice Island	1.08	0.44		NR/31/31	0.07	RD 2023
Hotchkiss Tract	1.07	0.42		20	0.03	RD 799
Union Island	1.07	0.42		U/8	0.01	RD 1/2
Tyler Island	0.98	0.41		NR/60/60	0.07	RD 563
Canal Ranch	0.95	0.38		R/66	0.03	RD 2086
Terminous Tract	0.95	0.38		U/39	0.03	RD 548
Wright–Elmwood	0.91	0.37		U/4	0.01	RD 2119
McDonald Island	0.83	0.32		NR/25/25/30	0.05	RD 2030
Medford Island	0.83	0.32		NR/30/30	0.05	RD 2041
Rindge Tract	0.83	0.32		NR/27/27/27	0.03	RD 2037
Rio Blanco Tract	0.83	0.32		68	0.01	RD 2114
Dead Horse Island	0.78	0.30		NR	0.01	RD 2111
Holland Tract	0.73	0.29		NR/19	0.03	RD 2025
Eucalyptus Island	0.70	0.22	F	—	—	
Rhode Island	0.70	0.22	F	—	—	
Bouldin Island	0.70	0.22		R/32	0.03	RD 756
Byron Tract	0.70	0.22		12	0.03	RD 800
Empire Tract	0.70	0.22		NR/29	0.05	RD 2029
Staten Island	0.70	0.22		NR	0.05	RD 38
Coney Island	0.65	0.20		NR/11	0.01	RD 2117
Shima Tract	0.58	0.18		48	0.01	RD 2115
Shin Kee Tract	0.58	0.18		69	0.03	
Bethel Island	0.48	0.16		21	0.05	
Drexler Tract	0.45	0.15		?	0.05	RD 2039
Fay Island	0.37	0.14		?		RD 2113
King Island	0.33	0.13		NR/28	0.01	RD 2044
Orwood Tract	0.28	0.11		U /15	0.03	RD 2024
Little Mandeville Island	0.20	0.01	F	—	—	RD 2118
Mildred Island	0.20	0.01	F	—	—	RD 2021
Bacon Island	0.20	0.01		NR/17	0.05	RD 2028
Jones Tract	0.20	0.01		R/24	0.05	RD 2038/2039
Palm Tract	0.20	0.01		R/16	0.03	RD 2036
Quimby Island	0.20	0.01		NR/22	0.07	RD 2090
Victoria Island	0.20	0.01		U/9	0.05	RD 2040
Woodward Island	0.20	0.01		R/14	0.03	RD 2072

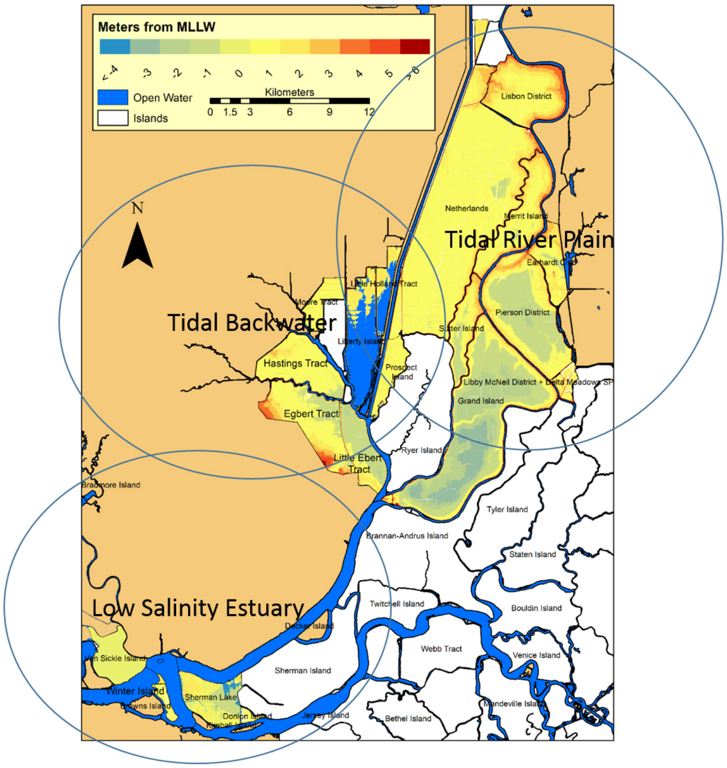

Figure 8 Regions dominated by high-scoring polders on the NSBI

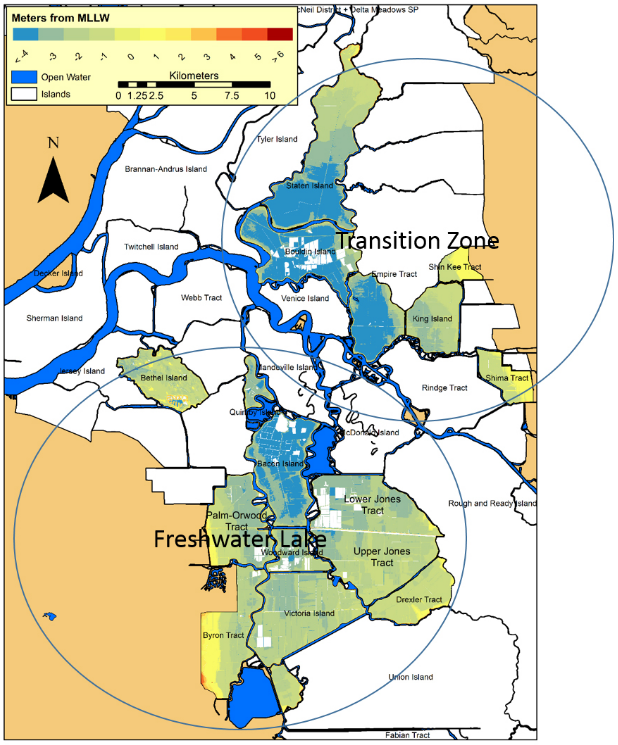

Figure 9 Regions dominated by low-scoring polders on the NSBI

the bottom 25% because of the large amount of flow energy that is available to them, which could be used to engineer different habitat values post-flooding. In contrast, polders north of the San Joaquin are adjacent to channels with relatively low flows, especially in the easternmost tracts; they are shallower toward the east side of the region, and form an elevational gradient to above sea level (from −5 m to 4 m from MLLW). Most of the middle-scoring tracts are located toward the central and southern part of the Delta.

DISCUSSION

Evaluating Regional Differences

The NSBI scores suggest Delta polders are clustered in five geographic regions with distinctive ecological functions. The highest scores describe polders that, if flooded, would be more likely to support restoration and conservation goals for native fish. At the other extreme, the lowest-scoring polders would be unlikely to provide many benefits in terms of restoration goals for native species. Taking into consideration the NSBI scores and the geomorphology of the regions, the north Delta may be best suited to tidal river plain restoration activities, the (CLC) as a tidal backwater system, the Confluence as a low-salinity estuary mouth, the south Delta as a freshwater lake, and the east Delta as a transition zone between lotic (north Delta) and lentic (south Delta) environments.

Evaluating the ecological potential of currently non-flooded tracts allows the risks and consequences of flooding to be better assessed. Polders that are currently flooded provide some validation for these categories. The CLC contains Liberty Island, the Confluence includes Sherman Lake, and the south Delta contains Franks Tract and Mildred Island. The high scores of Liberty Island and Sherman Lake, although driven by different factors, are supported by surveys of fish community assembly on those tracts, which show comparatively high proportions of natives (M. Young and D. DeCarion, 2010–2017 unpublished data, see "Notes"). Likewise, low scores for Mildred Island and Franks Tract correspond to low proportions of native fishes found on those

Table 5 Trade-offs in regional attributes and ecological outcomes

Region	Flow	Elevation	Turbidity	Mean score	Ecological outcome
Confluence	High	Moderate	Moderate	2.18	Low salinity estuary
CLC	Low	Shallow	High	1.86	Tidal backwater
North Delta	High	Shallow	Low	1.60	Tidal River plain
Eastside	Moderate	Moderate	Low	1.02	Transition zone
South Delta	Low	Deep	Low	0.78	Freshwater lake

tracts (and high proportions of aliens) (Nobriga et al. 2005; Nobriga and Feyrer 2007; J. Durand, M. Young, and D. DeCarion, 2010–2017 unpublished data, see "Notes"). It is reasonable to conclude that non-flooded polders in these regions, with similar scores, may produce similar outcomes when flooded.

The highest-scoring polders were, in general, clustered in the region of the Confluence. The dynamic complexity and variability of this habitat, and the influence of salinity, suggest that it will behave more like a low-salinity estuary mouth than any other Delta region. This area is typified by moderate polder depth, suggesting high phytoplankton production will occur here at times. However, high flows combined with high exchange may cause plankton dispersal, suggesting that it is poor habitat for planktivorous fish. If flows are constrained by dikes to increase or vary water residence time on polders, then phytoplankton productivity may increase, but, given high clam abundance and river flows in the region, both pelagic productivity and biomass will be low.

Sherman Lake, situated at the Confluence, supports this prediction. It is exposed to the high flows of the region, but is also somewhat constrained by old levees, emergent wetlands, and reinforced Sherman Island levees. As a result, Sherman Lake has extensive summertime SAV patches, punctuated by open water (personal observation). The combination of structure and abundant detrital carbon results in a high abundance of epibenthic invertebrates. Plankton biomass is low, probably because of high dispersal and advection, and because of nearby high-density patches of clams (personal data). Planktivorous fish are rare, but the ratio of adult native to alien fishes is relatively high, perhaps the result of brackish water and high flows, which are likely to limit centrarchid fish recruitment.

The second-highest scoring polders tended to be clustered in the north Delta region. High flows from the Sacramento River, moderate turbidity, and intermediate elevations cause this region to resemble tidal river plain habitat, which can provide refuge and foraging opportunities for outmigrating salmon juveniles and other riverine species. In the north, polders are generally shallow, deepening to the south. High flows will tend to disperse plankton, but emergent vegetation will provide organic matter and structure for epibenthic invertebrates.

No tracts are currently flooded in the region, but Prospect Island will likely be the first, as part of Delta Restoration efforts (EcoRestore, *http://resources.ca.gov/ecorestore/california-ecorestore-projects/*). Prospect, Lisbon, Netherlands, and Merrit polders are all at intertidal elevations. Grand and Pierson islands are sufficiently subsided that they offer less intertidal structure and restoration opportunities; however, they may work effectively in conjunction with shallower flooded polders as open-water habitat, complemented by intertidal and emergent marsh. A key unknown is the response of invasive aquatic plants (mainly *E. densa*) and clams (*C. fluminea*) to new aquatic habitats in this region. Nutrient inputs will be high, reflecting conditions in the Sacramento River. Currently, the southern half of Prospect Island is partially open to tidal incursion, and has a thick bed of *E. densa* where it is flooded. This is likely to expand once the island it open to full tidal exchange.

The CLC, with low-energy tidal flows, shallow depths, and high turbidity, has attributes that resemble a tidal backwater slough. The dominance of tidal energy may promote mixed residence times across the landscape (Durand 2015), promoting pelagic food webs. Low background nutrient levels may limit invasions of *C. fluminea* and *E. densa* to some degree; however, this is currently a key uncertainty. The elevation gradient of the region will support the development of emergent marsh adjacent to open shallow water in places, supplying organic carbon to the microbial food web. Shallow water tule and edge structure will provide a substrate for epibenthic invertebrates. The region could provide good habitat for planktivorous, benthic, and piscivorous fish.

Liberty Island, the major flooded polder in the CLC, offers some evidence to support this prediction. Liberty Island sits in the middle of a complex of historical and created sloughs, including Cache Slough, Lindsey Slough, Shag Slough, the Toe Drain, and the Sacramento Deep Water Ship Channel. The north end of Liberty Island has an emergent freshwater marsh, dominated by tules, that is directly connected to the open water of the tract. Liberty Island undoubtedly receives ecological benefits from the heterogeneity of the region, including cold water refugia, inputs from the marsh, and pelagic production from adjacent regions. Pulses of high-nutrient water from the Sacramento River and the Yolo Bypass produce ephemeral phytoplankton blooms. It has less extensive SAV and clam abundance than other flooded tracts to the south. Nitrogen inputs are limited in this area relative to other regions in the Delta and appear subject to rapid draw-down. Liberty Island appears to have a high proportion of native to alien fishes, particularly in wet years. Abundant planktivores are found in the region, including Delta Smelt, Threadfin Shad and American Shad, consistent with NSBI predictions (Lindberg and Marzuola 1993; Sommer et al. 2011; Sommer and Mejia 2013).

The south Delta contains many of the lowest-scoring polders. These are characterized by low flows, deep subsidence, and low turbidity, attributes resembling a freshwater lake. Flows will be flood-dominated because of water export. The depth, a mixed water column, high concentrations of nutrients, high densities of clams, and extensive SAV will tend to inhibit phytoplankton production and bloom formation. Food webs will be driven by particulate organic matter and microbial production, supporting adult fish. Water temperatures will tend to be warm because of limited flow and exchange. These polders will be dominated largely by alien fish species that prefer warm, clear water and vertical structure.

Franks Tract and Mildred Island, both flooded, characterize this region and are consistent with NSBI predictions. Franks is less deep than Mildred, and has patchy distribution of SAV. Mildred is ringed by a band of SAV along the shallower edge. The open water and adjacent sites have high densities of clams (Lucas et al. 2002). Mildred Island has been known to have occasional phytoplankton blooms, but these are consumed upon export by high densities of clams in residence adjacent to the polder. SAV and particulate organic matter promote epibenthic invertebrates. Piscivorous and benthic feeders perform well in these tracts (Nobriga et al. 2005; Nobriga and Feyrer 2007; M. Young and D. DeCarion, 2010–2017 unpublished data, see ”Notes”). Warm temperatures, abundant structure, and clear water favor alien centrarchids, including largemouth bass.

The east Delta will be characterized by moderate flows, moderate elevation, and low turbidity. NSBI scores are somewhat higher than the outh Delta’s. Although the east Delta will resemble the south Delta in many respects, the east Delta will be ebb-dominated rather than flood-dominated (because of differences in water operations), and sit adjacent to an elevation gradient into transitional intertidal and floodplain habitats. I characterized this as a transition zone because of the potential to capitalize on flow energy, seasonal floodplain activation as a food resource, and elevation to create unique outcomes. Left alone, polders here will be expected to follow a pathway similar to those in the south Delta. However, careful management of breaches, structure, flow, and residence time will create very different habitats. In addition, this region may lend itself to subsidence reversal management, such as that in progress on Twitchell Island. Such activities would help to create a barrier between polder ecosystems dominated by alien species in the south and the mixed-community polder ecosystems in the north and west Delta. There are currently no flooded tracts in this region, but the model suggests that most flooded polders would support a mix of native and alien benthic and piscivorous fishes. The effectiveness of the polders would be determined, in part, by design and management decisions.

Limitations of the Study and Further Research

The NSBI was designed to evaluate the response of individual polders to flooding—something that may be inevitable for many of them—and the environmental consequences of such an event. I based the three metrics used here upon available data that were suitable to generalization over a large area. However, these generalizations are bound to be conditional for each polder site; to understand outcomes more precisely would involve detailed modeling. Additional metrics that will bear consideration for each polder will be connectivity and geomorphology, physical structure, nutrient inputs, temperature range, and salinity. I discuss these below.

Exchange and Geomorphology

The exchange of nutrients and production is a function of the number of breaches, as well as the shape and depth of the polder. Long profiles relative to the tidal exchange create mixed residence times and mechanisms for particle retention within the sloughs (Enright et al. 2006, unreferenced, see "Notes"; Enright 2008, 2010, unreferenced, see "Notes"; Enright et al. 2013). Rates of exchange that are variable are likely to best support restoration habitat. Complete (high) exchange is unlikely to support sufficient residence time to build up blooms of plankton. Low exchange may support blooms, but will cause drawdown of nutrients without replenishment, and limit distribution of food to other regions (i.e., open habitat) where it can be used by grazers and predators (Lucas et al. 1999a, 1999b, 2002; Ahearn et al. 2006; Doyle 2010; Lucas and Thompson 2012). Polders that support exchange which varies on a lunar tidal scale are likely to support pelagic production and fishes.

Physical Structure

Structure may consist of dike edges, SAV, wood, or any other surface. Epibenthic invertebrates use structure for a substrate. Predator and prey fishes alike use structure for refuge and predation, including structure provided by SAV. Thick stands of *E. densa* can favor alien fishes over natives (Brown 2003; Feyrer 2004; Nobriga et al. 2005; Nobriga and Feyrer 2007). Complex, varied structure, such as fallen trees, or native SAV such as *Stuckenia* spp., offers opportunities for balanced interactions among trophic guilds to occur.

Nutrient Inputs and Phytoplankton Production

Much of the estuary is subject to high nutrient loads. Nutrient enrichment can create phytoplankton growth, yet blooms seldom occur in the estuary today, in part as a result of clam grazing. The clams are abundant and usually food-limited (Foe and Knight 1985), suggesting that they have the capacity to consume much of the available phytoplankton. Portions of the Delta tend to have less *E. densa* and fewer clams (Suisun Marsh, Liberty Island, the CLC). Phytoplankton blooms have been observed to occur under moderate nutrient conditions, but dissipate as they (1) run out of nutrients, (2) settle out of the water column to the sediment layer, or (3) become grazed by clams as they moved toward the western Delta.

Temperature Range

Thermal refuges have become more critical because climate change may increase summer surface water temperatures close to or beyond the physiological capacity of many native fish (Dettinger 2005; Dettinger and Culberson 2008; Nobriga et al. 2008). Deep pools offer cool temperature refuges that allow vulnerable fishes to survive.

Salinity

None of the Delta's fish species depend exclusively on brackish water, but salinity structures habitat in a way that promotes diversity. Most native species are remarkably tolerant to changes in salinity, while many invasives are less tolerant (Feyrer 2004; Feyrer

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et al. 2005, 2006, 2007; Nobriga et al. 2008). Tidal restoration projects in the low-salinity zone (i.e., values around 2 psu) are subject to varying salinity, which may preferentially support native species to some degree.

All of these factors will need to be modeled on a polder-by-polder basis to enable a clear prediction of how each will develop into aquatic habitat. Although such an approach is unpractical on a Delta-wide basis, it should be used to evaluate polders targeted for restoration by breaching, or polders that are at high risk of flooding with low probability of repair. These latter cases are discussed in the next section.

Cross Comparison of Economic and Logistic Rankings with Habitat Scoring

Some polders have been prioritized for repair and preservation in case of flooding because they are important for urban populations, salinity management, or water export. Others may be repaired because of the economic value of the land.

Of the polders with high NSBI scores, a number are already flooded, including Sherman Lake, Liberty Island, and Little Holland Tract. Van Sickle Island is a managed wetland. The non-flooded tracts are used primarily for agriculture, although Prospect Island is planned to be flooded for use as native fish habitat. Both the probability of failure and the prioritization of repairs for non-flooded islands in this group are low. This suggests that the rare breach and flood on these islands will tend to become permanent. The exception to this may be Van Sickle Island, which, because it is managed for ponds and waterfowl, and is quite shallow, may be repaired nearly as easily as it is breached. For the other islands, repair, de-watering, and rehabilitation once flooded may not be economically feasible.

Many of the polders with the lowest NSBI scores have low repair prioritizations, and generally high probabilities for failure, suggesting that a number of these tracts may also fail and not be repaired. As suggested above, it would be helpful to use a full suite of modeling tools to carefully evaluate these high-risk polders for environmental outcomes. This would allow managers and stakeholders to begin planning—including approaches to manipulate the site to reduce ecological effects—before catastrophic flooding.

Designing Polders

Through management and proper habitat design, the function of flooded polders may be improved, particularly if ecological goals are scaled suitably to the available ecosystem. Design goals (that is, measurable outcomes) for flooded polders may include increased pelagic productivity, reduced extent of alien SAV, reduced alien clam abundance and distribution, and a suite of native or desirable alien fishes. Not all of these desirable outcomes are attainable from any given flooded polder. Some of these habitat outcomes may support restoration goals for the Delta, while others will be neutral or antagonistic to those goals. Restoration goals should be chosen that scale to the physical constraints of the site, and which work in synergy with adjacent aquatic habitat.

To maximize expensive investments for longevity and function, most flooded polders will require careful planning, design, and management. Planning will need to incorporate regional concerns. The increase in volume of aquatic habitat has implications for tidal excursion and directional flows. Undesirable species may encroach, complicating recovery efforts for endangered species, and water quality may be affected, particularly if hydrodynamic shifts increase salt incursion and nutrient availability. Finally, planning must also anticipate risks to adjacent non-flooded polders whose levees may be subject to erosion from increased wave action and underground seepage. Environmental reviews and permits will be required to satisfy legal requirements under the Endangered Species Act, the Clean Water Act, the California Environmental Quality Act, the National Environmental Protection Act, and the Delta Protection Act (Suddeth 2011).

Design and management of flooded polders will vary depending upon desired outcomes. As presented here, regional constraints will be critical to the success of outcomes. For example, in a tidally driven area like the CLC, polders that are designed to support pelagic food webs will require scaling to the tidal energy available in that region. However, in a high-flow region like the Confluence, breaches may need to be replaced with configurable gates to control flow rate. In the south Delta, it may be desirable to breach tracts and allow an ecosystem dominated by aliens to colonize it, creating lake-like environments dominated by invasive aquatic plants and alien fishes like largemouth bass. Passive designs, while inexpensive and not incompatible with recreational uses, still incorporate considerable risks if unintended consequences occur. For example, infestations of *E. densa* that impede navigation, or blooms of harmful algae such as *Microcystis aeruginosa* that threaten public health, may be difficult to manage without appropriate management and supporting design features.

Design tools can include the number and location of breaches, the installation of maneuverable gates to manage water exchange, the creation of starter channels to promote water flow paths, the addition of sediment berms to support emergent vegetation and control water flow , installation of facilities to support recreation and science, the eradication of undesirable vegetation, and the planting of desirable vegetation. Because of unknowns, features to support adaptive management experiments would be highly desirable, including subdividing tracts into separate ponds that could be used for comparative treatments.

Figure 10 demonstrates a flooded polder designed to support adaptive management by creating three parallel ponds that can be used to deploy experimental treatments. Configurable gates at strategic locations allow water flow to be manipulated. For example, gates can be set to drive one-way flow pulses scaled to tidal cycles, which can slow the movement of water across a site, potentially increasing the production and accumulation of pelagic food. An alternative setting leaves gates open to bi-directional flows, leaving the site completely open to tidal exchange, which may facilitate passage of fish, but also increases rapid dispersion and advection of food resources. A third option could allow mimicry of historic slough variability and function by allowing water to move through side gates and hold in different ponds. Gate manipulations offer the opportunity to maximize desired outcomes and to run experiments that measure ecosystem response in water quality, food production and fish usage. Different configurations would allow experimental comparisons between treatments; for example, pond versus slough performance.

Figure 11 shows a more highly managed option that might be suitable for the transition zone in the east Delta. The design also incorporates replicate treatments, in this case two built sloughs with terminal, gated ends, which can be spilled into a deeply subsided floodplain. The sloughs can be manipulated to test the effect on production of residence time, tidal exchange, or nutrient additions. The floodplain would be intensively managed with tules, rice, or some other wetland vegetation to support soil accretion.

CONCLUSIONS

Regional differences are important for managing current and future flooded polder habitats in the Delta. Flooded polders in the north Delta and CLC will be best managed as river floodplains or tidal sloughs. The Confluence, with intensive management, may be operated as productive open-water estuarine habitat. The south Delta has little potential for conservation, so it may be best to manage it as a novel lake ecosystem, with an emphasis on preserving water transport and recreation. The transition zone in the east Delta serves as both connector and buffer between these two dramatically different ecosystems. Decisions on flooded polder management should be considered within this regional context.

Decommissioning and flooding of polders throughout the Delta will occur by accident or intention. Unfortunately, the polders most likely to flood and become abandoned also offer the fewest conservation benefits, particularly in the south Delta. There are few economic incentives to prepare for aggressive management of these tracts, unless the cost of future risks is considered. These risks include barriers to navigation, development of harmful algal blooms, water quality degradation, and risks to threatened and endangered species. Investments in Delta polder management must be considered not only in the light of land value, but also in terms of potential losses and gains.

It is worth noting that polders planned for restoration benefits may be benign or productive after initial

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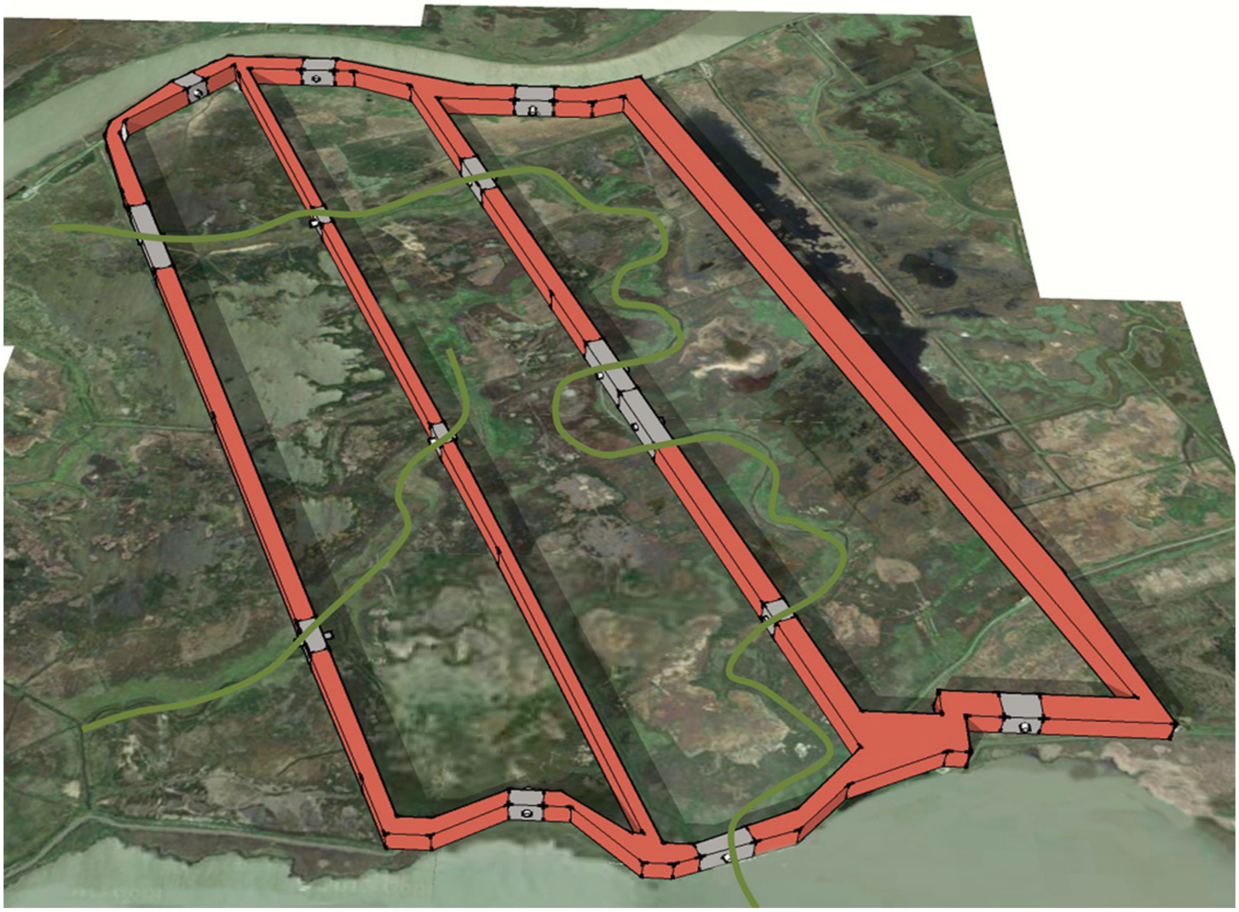

Figure 10 Dike and gate configuration so support one-way flows across replicate ponds, or tidal, two-way flows along historic slough pathways

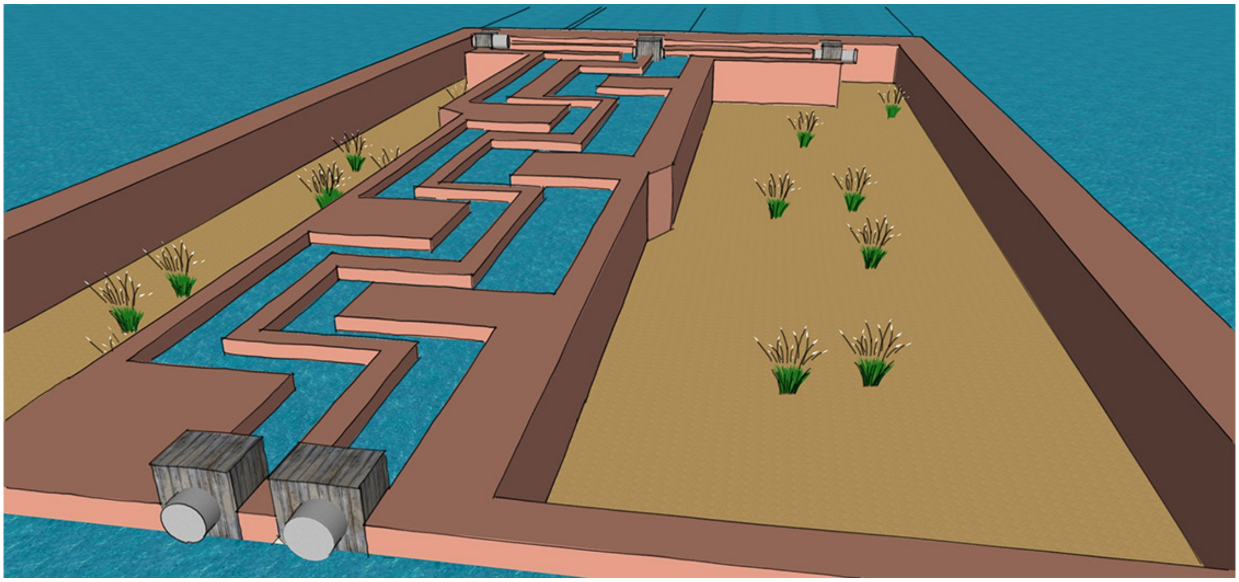

Figure 11 Configurable sloughs with spillways to experimental floodplain on a deeply subsided island

flooding, but may lose their conservation potential without proper interventions. Up-front investment and continuous ongoing management will be required for all subsided polders, whether flooded or not. The tools of adaptive management offer the benefits of strategic planning, investment, and infrastructure design and are better options for risk management, better habitat and recreation opportunities, and increased scientific understanding.

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