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Simulation of flood impact and habitat extent for a tidal freshwater marsh restoration

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Abstract

It has been estimated that over 90% of the tidal freshwater wetlands of the Sacramento-San Joaquin Delta region in California, USA, have been leveed, removing them from tidal and floodwater inundation. One alternative for restoration of tidal freshwater marsh ecosystems is to reconnect regions currently managed for agricultural purposes to the adjacent rivers and sloughs. Two elements of such restoration efforts that have not been adequately addressed are the impact that restoration efforts are likely to impose on flood stages, and the extent of various habitat types that may develop. This study tests the hypothesis that habitat restoration and flood mitigation can be compatible. MIKE 11, a one-dimensional, unsteady hydraulic model is used to evaluate the flood stage impacts of five restoration scenarios for the McCormack-Williamson Tract, located in the northern Sacramento-San Joaquin Delta of California, USA. In addition to quantifying flood impacts, model results are used to quantify the volume of tidal exchange, and integrated with GIS to quantify the potential areal extent of subtidal, intertidal, and supratidal habitat zones within the project. The results indicate that the restoration would provide a mosaic of habitat types, and have a minimal adverse impact upon flood stages during a range of flooding conditions.

Keywords: Sacramento-San Joaquin Delta; Freshwater tidal marsh; Wetland restoration; Hydraulic model; GIS; Hydrodynamics; Flood pulse; Inundation

1. Introduction

Over 50% of the wetland ecosystems throughout the conterminous United States have been severely degraded or destroyed for the purpose of agricultural or urban land uses (Dahl and Allord, 1996). A realization of their irreplaceable ecosystem functions and value has created nationwide interest in restoration and rehabilitation of many of these damaged ecosystems (U.S. Environmental Protection Agency and U.S. Department of Agriculture, 1998). One such system, the Sacramento-San Joaquin Delta of California, USA, previously one of the richest ecosystems in the Americas, currently exists in a highly altered state due to: (1)

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the reclamation of tidal wetland areas for agricultural purposes (Atwater, 1980); (2) changes to the seasonality, magnitude and routing of water flow (Arthur et al., 1996); and (3) exotic species invasion and introductions (Cohen and Carlton, 1998). It has been estimated that over 90% of the tidal freshwater wetlands of the Delta region have been leveed, removing them from tidal and floodwater inundation (Simenstad et al., 2000). In an effort to restore ecosystem health, a program comprised of over 20 state and federal agencies, the California-Federal Bay/Delta Program (CALFED) has proposed the restoration of tidal freshwater marsh ecosystems by reconnecting regions currently managed for agricultural purposes to their adjacent rivers and sloughs (CALFED, 2000).

Hydrology is the primary forcing function in wetland ecosystems, and is an essential element in successful wetland restoration projects (Mitsch and Gosselink, 2000). In wetlands, the dynamics of inundation have been shown to dictate the interdependence between hydrological and biological processes (Junk et al., 1989). In tidal marshes, tidal inundation and exchange determine the composition and distribution of vegetation (Roman et al., 1984; Rozsa, 1995; Pasternack et al., 2000), invertebrate, bird, and nekton communities (Allen et al., 1994; Raposa and Roman, 2001). In addition, tidal inundation affects sedimentation processes (Anisfield et al., 1999; Pasternack and Brush, 1998, 2001), sediment biogeochemistry (Anisfeld and Benoit, 1997; Portnoy and Giblin, 1997; Portnoy, 1999; Knight and Pasternack, 2000), and water chemistry and quality (Portnoy, 1991; Roman et al., 1995).

Wetlands are best known for their habitat functions, however they are also thought to provide important hydrologic functions, such as flood control (Novitzki et al., 1996). The potential impact of tidal freshwater marsh restoration on flood stages is an important element of restoration efforts that has not been adequately addressed. While the flood peak reduction of a wetland in a single stream is readily apparent, when a wetland is located as part of a complex multi-channel system, restoration efforts can potentially have variable effects. This study tests the hypothesis that habitat restoration and flood peak mitigation are not mutually exclusive. A one-dimensional unsteady hydraulic model is used to evaluate the flood stage impacts of several restoration alternatives for the McCormack-Williamson Tract (MWT), located in the northern Sacramento-San Joaquin Delta (North Delta). In addition to quantifying flood impacts, the hydraulic model results are coupled with GIS to quantify the potential areal extent of subtidal, intertidal, and supratidal habitat zones within the wetland area for each alternative. The alternatives considered range from designs, which restore the entire tract to tidal marsh habitat to designs which partition the tract to allow for flood storage and continued agriculture. Features considered include weirs, levee breaches, levee removal, and internal levee construction in a variety of configurations.

1.1. Study area

The MWT is a 652 ha parcel located in the northern portion of the Sacramento-San Joaquin Delta of California, USA (Fig. 1), which historically supported tidal freshwater marsh and riverine floodplain habitats (USGS, 1911; Brown and Pasternack, 2004). In 1919, the natural levees around the tract were raised in an effort to reclaim the land for agricultural uses, removing it from regular tidal and floodwater inundation (State of California Reclamation Board, 1941). Since then, these levees have been raised, improved, accidentally breached and repaired a number of times. The Nature Conservancy purchased the tract in 1999, for the purpose of restoration.

1.1.1. Hydrology and hydraulics

Several streams with headwaters in the western slope of the Sierra Nevada mountain range discharge to the study area, including the Cosumnes River (draining an area of 2468 km^2), Dry Creek (917 km^2), and the Mokelumne River (1927 km^2). The Cosumnes River is one of the last unregulated rivers in California, maintaining its natural flood regime, sending flood pulses downstream in response to major precipitation events. The Mokelumne River is regulated by several dams, which impound flood flows for power generation and municipal water supply. Dry Creek historically was a tributary to the Mokelumne River, however because of anthropogenic influence it now feeds the Cosumnes River and provides large flood pulses in response to rain events.

The MWT is located in the midst of a hydraulically complex system. Tidal and fluvial forcings drive water through a heavily manipulated system of branching channels and dead end sloughs, confined by levees,

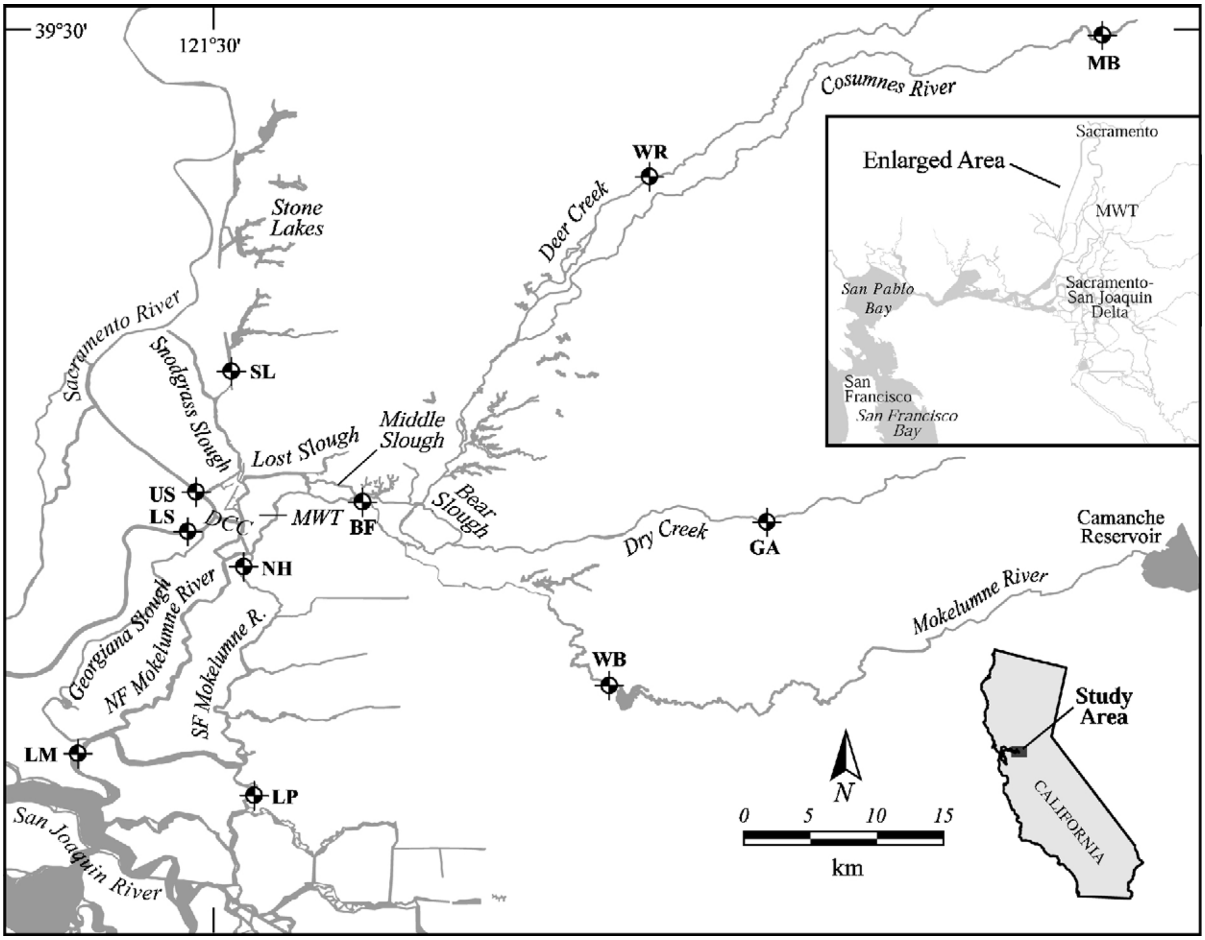

Fig. 1. Regional and local setting of the McCormack-Williamson Tract, and location of gages used for boundary conditions and internal validation points. Model result validation and scenario comparison is conducted at Benson's Ferry (BF) where the Cosumnes River converges with the Mokelumne River and at New Hope (NH) where the North and South Forks of the Mokelumne River diverge. Model boundary conditions are labeled as follows: MB: Michigan Bar on the Cosumnes River, WR: Wilton Road on Deer Creek, GA: Galt on Dry Creek, WB: Woodbridge on the Mokelumne River, SL: Stone Lakes Outlet at Lambert Road, US: Sacramento River above the Delta Cross Channel (DCC), LS: Sacramento River below Georgiana Slough, LM: Lower Mokelumne River at Georgiana Slough and LP: Little Potato Slough below Terminous.

and subject to backwater conditions caused by road crossings and railroad embankments. The tract lies near the upstream extent of tidal fluctuation, experiencing a mixed semi-diurnal tidal pattern with approximately two high tides and two low tides daily, with an average tidal range during low river flow conditions of 0.94 m (NOAA-NOS, 2002). During the winter and spring, storm and snowmelt events contribute additional influence to the hydraulics of the regional system. The operations of water resource facilities, Mokelumne River reservoir releases and Delta Cross Channel (DCC) gates, also affect regional water levels and system hydraulics. The DCC gates allow for the introduction of Sacramento River water into Snodgrass Slough, which ultimately connects to the Mokelumne River.

The North Delta has experienced significant flooding on several occasions. Limited conveyance in the Mokelumne River and Lost Slough in the MWT vicinity create a bottleneck in the regional hydraulics, forming a backwater effect east of the MWT during large flood events. During two recent instances, the large flood events of 1986 and 1997, the eastern levee of the MWT failed. On both occasions, floodwaters inundated the MWT and surged to the southern portion of the tract. This pulse of floodwaters caused an inside out failure of the levee, returning water into the already swollen North and South Forks of the Mokelumne River, further compromising downstream levees (U.S. Army Corps of Engineers, 1988). Due to its geographic location, and flooding history, any manipulation to the manner in which water moves around and through the MWT will likely impact flood stages and flows.

1.1.2. Historic ecology

When attempting to restore an ecosystem, it is imperative to understand the pre-disturbance state of the system, with regards to the physical processes, which shaped the biotic components of the ecosystem. Prior to the historic damming, draining, and levee building which created the current delta system, the Central Valley was dominated by floodplain process of the Sacramento and San Joaquin Rivers and their tributaries. Over bank flooding created natural levees which isolated immense tracts of standing floodwaters known as “tulares” (Thompson, 1960), which supported stands of bulrushes, tules and cattails (*Scirpus* spp. and *Typha* spp.) (Katibah, 1981). In addition to the seasonal lakes and flood basins, the tributary streams supported extensive riparian forests, which included valley oak (*Quercus lobata*), California sycamore (*Platanus racemosa*), Fremont cottonwood (*Populus fremontii*), box elder (*Acer negundo* var. *californicum*), black walnut (*Juglans californica*) and willow (*Salix* spp.) (Katibah, 1981; Strahan, 1981). These floristic communities evolved in response to the hydrologic conditions in the region, manifested by topography created by geomorphic processes and subsequently the frequency of inundation. It is therefore pertinent to understand the potential inundation dynamics of a site when attempting to restore it.

Located at the upslope fringe of the Sacramento-San Joaquin Delta, the current topography of the interior of the MWT ranges from −0.9 m to 1.5 m in elevation National Geodetic Vertical Datum (NGVD) as shown in Fig. 2 (California Department of Water Resources, 1992, 2002). Levee heights range from 4.1 m to 7.0 m (California Department of Water Resources, 1992, 2002). This range of elevation within MWT provides the potential for the creation of tidal freshwater marsh,

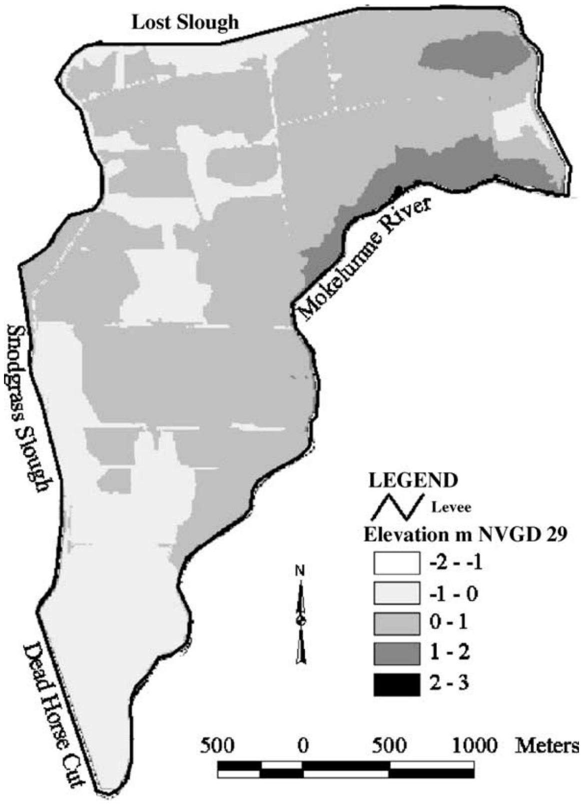

Fig. 2. The current non-levee topography of the McCormack-Williamson Tract ranges from −0.9 m in the southwest to 1.5 m in the northeast. Levee heights range from 4.1 m at the southern end to 7.0 m at the eastern border. The tract in its existing condition is partitioned into several agricultural cells, graded for irrigation and drainage.

seasonally inundated floodplain, and shallow open water habitat types without the need for material import and land surface grading. The areal extent of each of these habitat types will undoubtedly change as the tract evolves biologically and morphologically, but will initially be determined from the existing topography, and the degree of connectivity of the MWT to the adjacent river channels. The size, shape, elevation, and location of the levee breaches will determine the degree of connectivity to the surrounding river network.

1.2. Scenario descriptions

Several potential restoration configurations, or scenarios, have been developed (Fig. 3). Each scenario opens a portion of the tract to tidal and flood pulse

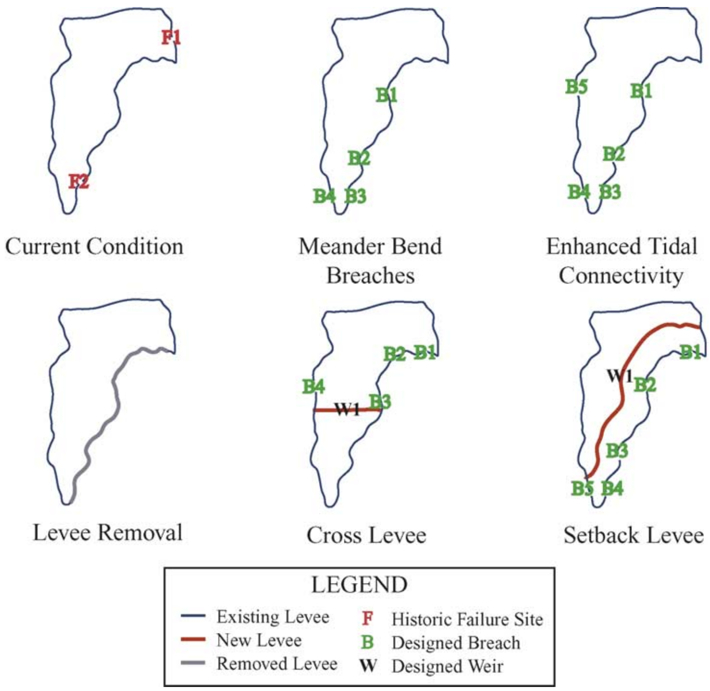

Fig. 3. Five scenarios in addition to the current condition configuration are considered. Meander bend breaches, enhanced tidal connectivity and levee removal scenarios open the entire tract to tidal and flood pulse inundation. Cross levee and setback levee scenarios partition the tract with low internal levees, which are overtopped in large flooding events. In the current condition configuration, levee failures only occur during large-rare flood events.

inundation restoring physical process to stimulate the rehabilitation of shallow water, tidal marsh and riverine floodplain habitat types. Beyond habitat restoration, an objective of each scenario is the avoidance of the flood surge caused by unplanned rapid levee failures as observed in 1986 and 1997 and to ensure that flood peaks upstream and downstream of the MWT are not inadvertently increased due to changes in the levee configuration. Breaches along the Mokelumne River are located downstream of meander bends to encourage the recruitment of sediment (Florsheim and Mount, 2002; Cheong et al., 2005). For all breaches the base elevations are chosen to correspond to the local land surface behind the levee at each location.

MWT in its current condition provides a baseline for the comparison of the five scenarios. During small flood pulses, like those which occurred in the winter and spring of 1998, 1999, and 2000, the MWT levees remain intact and prevented inundation, however in 1986, two large back to back storms caused high river stages, resulting in levee failures (indicated by "F" in Fig. 3) and subsequent flooding on several islands and tracts in the North Delta.

The meander bend breaches (MBB) scenario is comprised of four 50 m wide breaches (sill elevations: B1 = 0.9 m, B2 = 0.0 m, B3 = −0.3 m and B4 = −0.6 m) located as shown on Fig. 3 opening the entire tract to tidal inundation. A variant of this scenario, enhanced tidal connectivity (ETC), is very similar to MBB, but with the inclusion of an additional large 300 m breach (B5 = 0.0 m) along Snodgrass Slough opposite the Delta Cross Channel. The objective of the additional large breach is to encourage the exchange of a large volume of water through the tidal cycle, without creating significant scour in the region adjacent to the breach.

The levee removal (LR) scenario involves the removal of the entire southeastern levee, which parallels the Mokelumne River, with the objective of enhanced flood conveyance. In addition, this scenario would allow for the development of a more natural riparian corridor along this reach of the Mokelumne River.

Two additional scenarios are considered which partition the tract, retaining a portion of the area for flood storage in large events, and continued farming. The cross levee (CL) scenario isolates a 200 ha region with a low (2.7 m high) east–west trending levee, and opens the remaining 450 ha region with three 50 m wide breaches (B1 = 1.5 m, B2 = 1.5 m and B3 = 0.9 m) along the Mokelumne River and one 100 m wide breach (B4 = 0.0 m) along Snodgrass Slough. The objectives of the cross levee are (1) the reduction of permanent open shallow water habitat, (2) flood storage for large events and (3) continued farming in the isolated southern region. The setback levee (SL) scenario contains a setback levee (3.0 m high) set 500 m back from the existing Mokelumne River levee, with the setback zone accessed with five 50 m breaches (B1 = 1.5 m, B2 = 0.9 m, B3 = 0.0 m, B4 = −0.3 m and B5 = −0.6 m). The objectives of this scenario are the expansion the flood corridor of the Mokelumne River with the retention of some land for agricultural uses and flood storage in large events.

2. Methods

The appropriate modeling approach is generally determined by (1) the purpose of the effort, (2) the amount of available data and (3) the degree of accuracy required (Bates and De Roo, 2000). Limited topographic and hydraulic gage data, when combined with the scale and complexity of the present study area, do not warrant more than a one-dimensional hydraulic modeling approach. While a two- or three-dimensional hydraulic model can more realistically model the dynamics of inundation, they require more topographic, boundary condition and internal observation data than are presently available.

To investigate the local and regional impact of various management scenarios on the MWT the MIKE 11 model is utilized. This is an unsteady, one-dimensional hydraulic modeling package, developed in 1987 by the Danish Hydraulic Institute, which has been used widely to simulate water levels and flow in river systems (Shumuk et al., 2000; Danish Hydraulic Institute, 2000; Blake, 2001; Mishra et al., 2001; Hammersmark, 2002). The GIS floodplain mapping and analysis module, MIKE 11 GIS, is used in this study to generate inundation statistics for the purpose of determining habitat extent.

When applied with the fully dynamic wave approximation, MIKE 11 solves the vertically integrated equations of conservation of mass and momentum (St. Venant equations), such that:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \tag{1}$$

and

$$\frac{\partial Q}{\partial t} + \frac{\partial(\alpha(Q^2/A))}{\partial x} + gA\frac{\partial h}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{n^2 gQ|Q|}{AR^{4/3}} = 0 \tag{2}$$

where Q is the discharge (m^3/s), α the vertical velocity distribution coefficient, A the cross section area (m^2), g the gravitational acceleration (m/s^2), x the downstream direction (m), h the stage above datum (m), t the time (s), n the Manning coefficient (m/s$^{1/3}$), q the lateral inflow (m^2/s), and R is the hydraulic radius (m).

Solutions for Eqs. (1) and (2) are based upon an implicit finite difference scheme developed by Abbott and Ionescu (1967), solved with a double sweep algorithm (Danish Hydraulic Institute, 2000).

The availability of hydraulic gage data dictated the domain of the hydraulic model. Data from 10 gages in the study area are utilized (Fig. 1), and have been provided by the United States Geological Survey, California Department of Water Resources, East Bay Municipal Utilities District, and Sacramento County. The model has six upstream boundaries and three downstream boundaries; and gage data from two internal locations, Benson's Ferry and New Hope, have been used as internal calibration and validation points in this study (Table 1). The data record from each of the hydraulic gages was not complete. The following assumptions were therefore made: Dry Creek at Galt (GA) was estimated at 40% of the Cosumnes River at Michigan Bar (MB) flow for 1998, 1999, and 2000 simulations; Little Potato Slough (LP) was set equal to Mokelumne River at Georgiana Slough (LM) data lagged by half an hour for all simulations; Deer Creek at Wilton Road (WR) was set at a constant stage of 16.4 m for 1986 simulations; and Stone Lakes Outlet

Table 1
Hydraulic gages, operating agency, and data type used as boundary conditions and internal comparison points in the hydraulic model

Hydraulic gage location[a]	Operating agency[b]	Data type/simulation year			
		1986	1998	1999	2000
Upstream boundary					
MB	USGS	Q, h	Q, h	Q, h	Q, h
US	USGS	–[c]	Q, h	Q, h	Q, h
GA	USGS	Q	e	e	e
WB	EBMUD	Q, h	Q, h	Q, h	Q, h
WR	SC	e	Q, h	Q, h	Q, h
SL	SC	e	h	h	h
Downstream boundary					
LS	USGS	h[c]	Q, h	Q, h	Q, h
LM	CA-DWR	h	h	h	h
LP	–	e	e	e	e
Internal					
BF	CA-DWR	h	h	h	h
NH	CA-DWR	h	h	h	h

For the location of each gage, refer to Fig. 1. Q: discharge, h: stage, e: estimated.
[a] MB: Michigan Bar on the Cosumnes River, WR: Wilton Road on Deer Creek, GA: Galt on Dry Creek, WB: Woodbridge on the Mokelumne River, SL: Stone Lakes Outlet at Lambert Road, US: Sacramento River above the DCC, LS: Sacramento River below Georgiana Slough, LM: Lower Mokelumne River at Georgiana Slough, LP: Little Potato Slough below Terminous, BF: Mokelumne River at Benson's Ferry, NH: S.F. Mokelumne River at New Hope Landing.
[b] USGS: United States Geological Survey, EBMUD: East Bay Municipal Utilities District, SC: Sacramento County and CA-DWR: California Department of Water Resources.
[c] For the 1986 simulations, the available stage data from RSAC 121 was used at the confluence with Georgiana Slough.

(SL) was assumed to have no flow in 1986 simulations (Hammersmark, 2002).

A total of 248 km of river channels and sloughs are included in the model, not including the extensive off channel regions, which are also incorporated in the model network. The model utilizes 454 in-channel and floodplain cross sections obtained from a variety of sources (Hammersmark, 2002). All cross section and boundary data are datum verified and translated as needed to the NGVD 29.

To properly evaluate the impacts of altering the current hydraulic system of the North Delta, a wide range of flows must be considered. The Cosumnes River is the dominant source of floodwaters to the North Delta region, therefore maximum Cosumnes River discharge (at Michigan Bar) for various flood pulses has been used as the primary distinguishing variable with recurrence intervals based upon a flood frequency analysis conducted by the USGS (Guay et al., 1998), for 91 years of data (1907–1997) using a log-Pearson type III distribution fit to the data for annual flood peaks. Based upon this analysis, four periods were chosen from 1986, 1998, 1999, and 2000. The return periods and peak flows are shown in Table 2. Although the 1986 flood corresponds to approximately a ∼25-year return interval, a second storm occurred just after the first storm introducing a substantially larger volume of water than would be expected for this recurrence interval. In addition to large flood pulses, low river flow (tidally dominated) conditions are simulated in each of the 4 years studied.

The model was calibrated against observed gage data at Benson's Ferry and New Hope for low flow,

Table 2
Maximum hourly averaged Cosumnes River discharge at Michigan Bar (see Fig. 1) and corresponding recurrence interval of the flood pulses modeled

Year	Maximum discharge[a] (m^3/s)	Recurrence interval[b] (years)
1986	1169	∼25
1998	928	∼10
1999	625	∼5
2000	334	∼2.5

[a] Maximum hourly averaged discharge.
[b] Recurrence intervals based a flood frequency analysis conducted by Guay et al. (1998), using 91 years of data (1907–1997).

tidally dominated river conditions and flood pulses. Initial estimates of roughness were made with reference to Barnes (1967) and Coon (1998). During the model calibration Manning's roughness values (n) were adjusted throughout various regions of the model resulting in values of $n = 0.04$ for the Cosumnes River, $n = 0.05$ for Deer Creek, Dry Creek, and the Delta Islands/Tracts, $n = 0.1$ for floodplain regions, and $n = 0.036$ for all other regions. A 4-month (January–April) period of 1998 was used for calibration, and the model was then validated with the first 4 months of 1986, 1999, and 2000. During the 1986 flooding event several levees failed in the North Delta. These levee failures were simulated with the Dam Break module of MIKE 11, with defined breach geometry and expansion rates. On the MWT, two levee failures were simulated, one at the top of the tract along the eastern levee, and one at the bottom of the tract along the southern end of the Mokelumne River (Fig. 1). Additional levee failures were simulated on Glanville Tract, Dead Horse Island, Tyler Island, and New Hope Tract (Hammersmark, 2002).

To simulate each of the scenarios, the model network was modified to represent each configuration. Breaches were modeled with "link channels" which are solved as flow across a broad crested weir. To maintain volumetric consistency the LR scenario was simulated with five 1000 m wide weirs set to the average land surface/floodplain elevation behind the existing levee.

2.1. Habitat zonation methodology

The MIKE 11 GIS software package integrates MIKE 11 hydrodynamic model output with the spatial analysis capabilities of ArcView (Environmental Systems Research Institute Inc.). The water levels calculated within MIKE 11 are projected as interpolated water surfaces over a digital elevation model (DEM). The difference between the simulated water surface and the DEM is determined based upon user defined flood depth increments. The area inundated by each increment is also calculated. It is important to acknowledge that the coupling of a one-dimensional hydraulic model with GIS merely projects the one-dimensional model results in two dimensions; it does not increase the complexity or dimensionality of the results.

The DEM is composed of a 9 m grid based upon a 1992 aerial photo survey of MWT topography resolved to a 0.3 m contour interval (California Department of Water Resources, 1992). MWT is currently used for agricultural purposes and has been partitioned into several agri-cells and graded for irrigation and drainage, allowing the interpolation of elevations between each contour interval. The DEM is modified to include a recent levee borrow pit in the northeast region (California Department of Water Resources, 2002), however further refinement of the surface was not done to include the many irrigation channels, which dissect the tract, as this study aims to quantify large areal differences between scenarios.

Several types of habitat are potentially obtainable on the MWT including subtidal, intertidal, supratidal, and wildlife friendly farming. Subtidal habitat refers to the region that remains inundated at mean lower low water (MLLW). Intertidal habitat is the region inundated at mean higher high water (MHHW) but not at MLLW. The region inundated by above average tidal levels and flood pulse flows, but not at MHHW is defined as supratidal habitat. Regions isolated by low levees, which are subject to flooding by larger less frequent events (CL and SL scenarios) are termed flood storage, but can also be used for continued wildlife friendly farming.

Water levels in the North Delta depend upon tide conditions, river discharge, and water resource facility operations (Delta Cross Channel gates and Mokelumne River reservoir releases). Published tidal characteristic values calculated from the New Hope gage data for the period of November 1978 to October 1979, for MLLW and MHHW are 0.07 m and 1.01 m NGVD, respectively (NOAA-NOS, 1982). These values were assumed to be representative indices of low and high water respectively. Using MIKE 11 GIS, flood inundation maps were created based upon model results for a specific moment in time. To convey the inundation statistics for each tidal index (MLLW and MHHW), exact tidal maximum and minimum moments from the current condition simulation were selected when the simulated stage at New Hope equals 0.7 and 1.1 m NGVD, the tidal index values for MLLW and MHHW. The inundation results from each scenario simulation for these moments were then used to quantitatively compare each scenario, and provide spatial inundation statistics. It is important to note that the potential habitat values presented for the various habitat types are calculated and provided for the evaluation and comparison of the various scenarios. These values should not

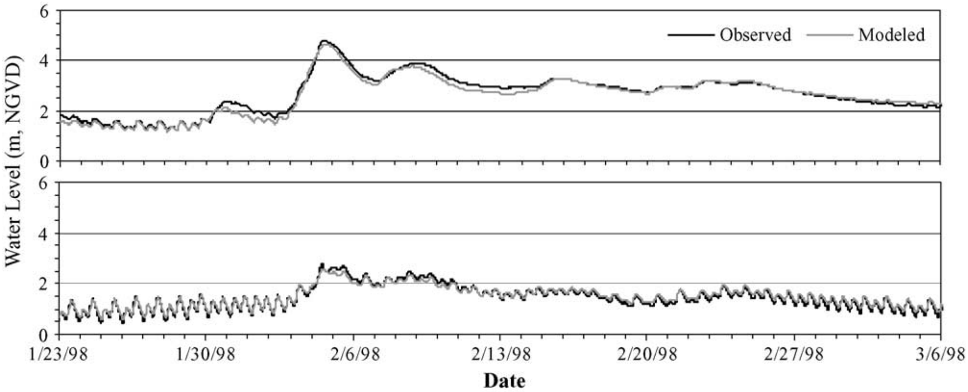

Fig. 4. Model results compared to observed hydraulic gage data at Benson's Ferry (top panel) and New Hope (bottom panel) for 1998 simulation used for calibration.

be considered absolute, as many factors including the sedimentation of the tract, and riverine influences upon the tidal levels in the study area will undoubtedly influence the distribution of habitats throughout MWT. Due to the varying magnitudes of tidal dampening caused by each scenario's configuration, each scenario yields different water levels within the tract and at New Hope at each representative tide. Thus, while each inundation map reflects the same moment or representative tide, each has a different water level value at New Hope, and throughout the tract.

3. Results

The hydraulic model has been applied to simulate the flooding period of 4 years: 1986, 1998, 1999, and 2000. Simulations begin in early January while river discharges are low and extend beyond the significant flood pulses of each year. Benson's Ferry and New Hope are used for comparison, based upon their locations above and below the MWT (Fig. 1). The model was calibrated to 1998 data and the remaining 3 years provided validation. Plots of water surface elevation versus time are provided in Fig. 4 for the major flood pulse of 1998 at each location, comparing model simulation results to observed gage data. Additional plots are provided in Fig. 5 for 6-week portions of the 2000, 1999, and 1986 simulations. During low river flow (tidally dominated) conditions, the model captures the magnitude and timing of the tidal oscillation at both locations (Fig. 5), although slight muting is observed. A comparison of simulated maximum water levels to observed data for each period modeled is provided in Table 3, as is the correlation of simulated results for the entire simulation period.

Changes to peak stage (maximum water level) relative to the current condition simulation at Benson's Ferry and New Hope for each scenario simulation and for each of the four storms simulated are shown in Fig. 6. Each of the scenarios reduces maximum water levels at Benson's Ferry for each of the flood events simulated. Reductions at Benson's Ferry range

Table 3
Error estimation for current condition model simulation results for each time period simulated at Benson's Ferry and New Hope, as compared to observed gage data

Simulation year	2000	1999	1998	1986
Benson's Ferry results				
Correlation coeficient[a]	0.978	0.978	0.962	0.989
Peak error[b]	−0.009	−0.070	0.024	−0.022
Observed MWL peak (m)	3.696	3.726	4.770	5.580
Simulated MWL peak (m)	3.735	4.006	4.657	5.706
MWL difference[c] (m)	−0.039	−0.280	0.113	−0.126
New Hope results				
Correlation coeficient[a]	0.961	0.953	0.978	0.979
Peak error[b]	0.007	−0.092	0.074	0.044
Observed MWL peak (m)	1.966	1.676	2.760	3.724[d]
Simulated MWL peak (m)	1.952	1.850	2.571	3.844
MWL difference[c] (m)	0.014	−0.174	0.189	−0.120

[a] Calculated by $\mathrm{Cov}(h_{\mathrm{obs}}, h_{\mathrm{sim}})/(\sigma_{h_{\mathrm{obs}}}\sigma_{h_{\mathrm{obs}}})$.
[b] Calculated by $(h_{\text{obs-max peak}} - h_{\text{sim-max peak}})/h_{\text{sim-max peak}}$.
[c] Calculated by $h_{\text{obs-max peak}} - h_{\text{sim-max peak}}$.
[d] Highest water level recorded in the incomplete gage record.

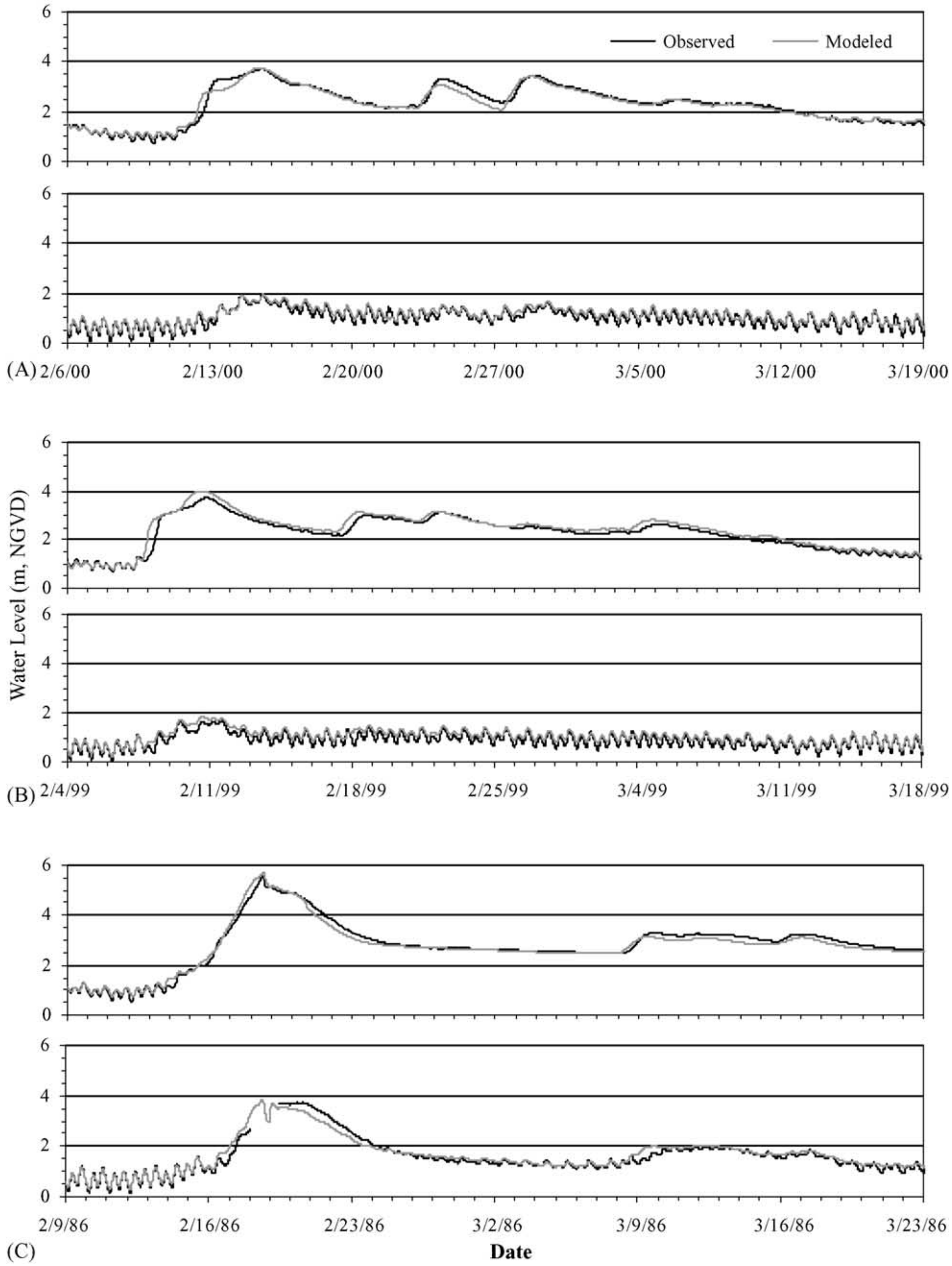

Fig. 5. Model results compared to observed hydraulic gage data at Benson's Ferry (top panel) and New Hope (bottom panel) for 3- and 6-week periods: (A) 2000, (B) 1999 and (C) 1986 flood pulses. New Hope gage data is unavailable from 2/18/86 1:00 a.m. to 2/19/86 11:30 a.m. due to damage caused by flood.

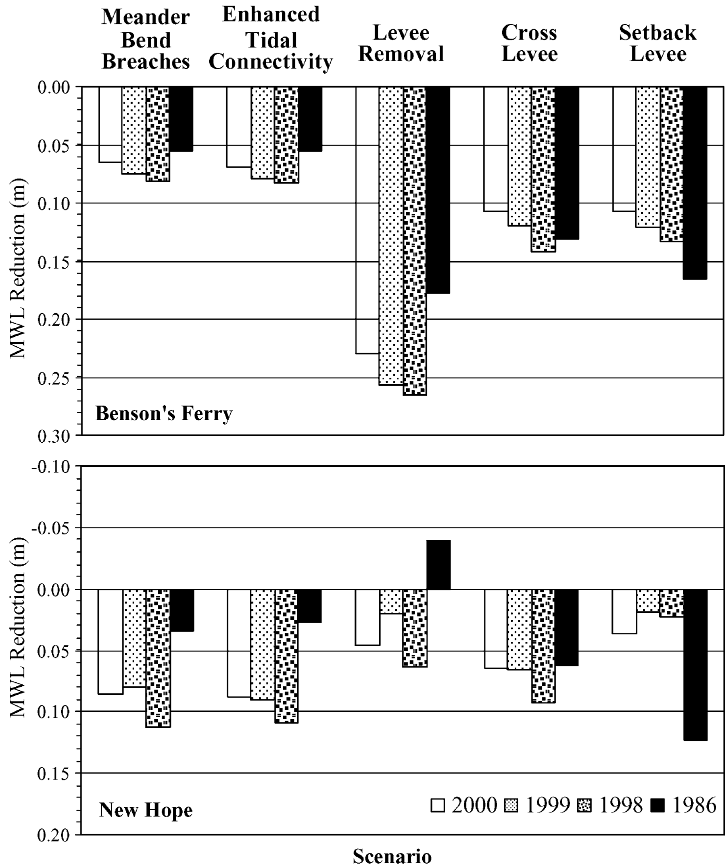

Fig. 6. Maximum water level (MWL) reduction (relative to current condition baseline) at Benson's Ferry and New Hope for each of the flood periods simulated with the hydraulic model. At Benson's Ferry, all scenarios reduce (0.06–0.27 m) maximum water levels in all periods simulated. At New Hope all scenarios reduce (0.02–0.13 m) maximum water levels, except the levee removal scenario in the 1986 event simulation, which raises the flood peak by 0.04 m.

from 0.06 to 0.27 m, with the LR scenario providing the largest flood peak reduction when observed at Benson's Ferry for all years. This result is due to the reduction of the constriction formed by the MWT levee, by providing off-channel areas for floodwaters to inundate, which in turn lessen peak river water levels in the backwater influence zone east of the tract. Most scenarios reduce water levels at New Hope as well, however the LR scenario increases maximum stage by 0.04 m at New Hope in the 1986 simulation. The configurations of MBB, CL and ETC scenarios maintain some degree of flow constriction, each providing flood peak reduction for all years, with the maximum benefit observed in 1998 for all three scenarios. The flood storage zones behind the low internal levees in CL and SL scenarios are only accessed in the 1986 simulations.

A comparison of the potential habitat extent, and volume of tidal exchange of each scenario is provided in Table 4 and Fig. 7. When compared to other scenarios analyzed, CL provides the potential for the largest area of supratidal/upland habitat at 104 ha (16% of the tract area), while ETC provides the largest area, 147 ha (23% of the tract area), of intertidal habitat. MBB and LR both yield the maximum areal extent of the subtidal habitat category, with both providing 424 ha (66% of the tract area) of this habitat type. When ranked by tidal exchange, ETC provides the largest volume of water exchanged (571,100 m^3) with LR and MBB following (504,800 and 484,000 m^3, respectively).

Table 4
Areal habitat extent and volume of tidal exchange for each of the scenarios as calculated with the hydraulic model and GIS

Scenario	Meander bend breaches	Enhanced tidal connectivity	Levee removal	Cross levee	Setback levee
Areal habitat extent (ha)					
Flood storage	0	0	0	199	386
Supratidal	97	98	93	104	63
Intertidal	119	147	123	60	94
Subtidal	424	395	424	277	98
Tidal exchange (m^3)					
Tidal cycle inflow	484,000	571,000	504,800	144,300	232,400

The scenarios, which open the entire tract to tidal inundation, result in a majority of subtidal/open water habitat. The scenarios, which create the largest volume of tidal, exchange result in the largest area of intertidal habitat. *Notes*: (1) Tidal cycle inflow volume calculated by summing breach discharge information for the two flood pulses of a typical tidal cycle.

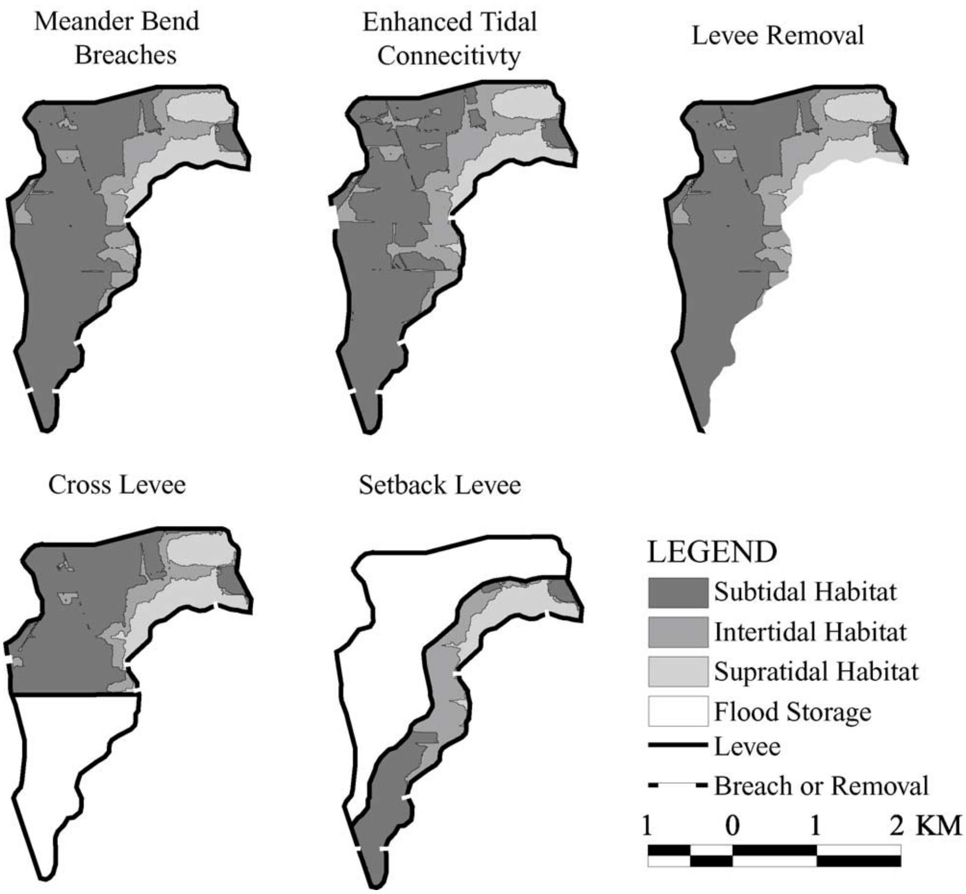

Fig. 7. Distribution and extent of subtidal, intertidal, and supratidal habitat zones of the simulated scenarios. For most of the scenarios a majority of the area open to inundation will provide subtidal habitat. The enhanced tidal connectivity scenario provides the largest area (147 ha) of intertidal habitat and the cross levee scenario the largest area (104 ha) of supratidal habitat. Refer to Table 4 for areal extent values for each scenario and habitat zone.

4. Discussion

The application of the Cosumnes–Mokelumne–North Delta Model to the investigation of ecological and flood benefits of various MWT management alternatives provides insight into the complex hydraulic nature of the North Delta, in addition to the opportunities for habitat enhancement in this region. Hydrodynamic results demonstrate that the model is able to simulate the hydraulics of this complex network through a wide range of flow conditions.

4.1. Flood benefits

Flood benefits vary, based upon the location of interest, with differing results observed above and below the tract. Each of the scenarios reduce the constriction formed by the MWT levee, by providing off-channel areas for flood waters to inundate, which in turn lessen peak river water levels in the backwater influence zone east of the tract. Maximum stage reductions at Benson's Ferry are gained by configurations with levee breaches/removal located further upstream along the Mokelumne River as seen in the CL, SL, and LR scenarios. Maximum results are achieved by scenarios with a higher degree of connectivity, a result of larger sections of levee removal in these locations, as seen in the LR scenario. Breaches or levee removal located further upstream reduce the constriction and reduced channel conveyance in Mokelumne River and Lost Slough, which the tract levees create.

Downstream of the project, at New Hope, most scenarios result in stage reductions for each of the periods modeled, however the LR scenario increases peak stage by 0.04 m in the largest flood event simulated, 1986. The configuration of the LR scenario allows the conveyance of a large volume of water through the tract, which moves the flow constriction downstream to below the tract, resulting in increased water levels in this region. The scenarios, which reserve a portion of the tract for flood storage (CL and SL), provide flood mitigation in all events, while the isolated flood storage zones are only accessed during the 1986 simulations. The SL scenario achieves a larger flood benefit than the CL scenario due to two factors, its larger flood storage area, and increased low levee height, which retains the flood storage until a later point in the hydrograph. Reduction values for CL at New Hope are less than those achieved with ETC when compared for years other than 1986.

4.2. Habitat potential

The results indicate the control that breach width, sill elevation and location exert upon the movement of water around and within the MWT. Tidal exchange and intertidal habitat are positively correlated such that scenarios, which encourage more tidal exchange with the surrounding hydraulic network, achieve a larger intertidal habitat zone. The configuration of ETC provides the most tidal exchange of the scenarios considered, and subsequently the largest intertidal area. The LR scenario ranks second in volume of tidal exchange and intertidal habitat, with MBB ranking third. These three scenarios (MBB, ETC and LR) all have breaches or levee removal in the southern end of the tract, where land surface elevations allow the breaches to actively convey tidal flows onto and off of the tract due to their large cross sectional areas.

Differences between each scenario's configuration translate to differences in tidal exchange and subsequently the areal extent of habitat. The large amount of levee removal in the LR scenario would appear to provide the largest amount of tidal exchange, however the natural levee and its elevated land surface along this side of the tract limit exchange. Table 4 illustrates that ETC with breaches located along Dead Horse Cut and Snodgrass Slough conveys a larger volume of tidal exchange with a smaller amount of levee removal when compared to LR. While MBB and ETC are similar, ETC includes an additional large (300 m) breach along Snodgrass Slough to enhance tidal conveyance, which provides more intertidal habitat. This indicates that MBB might provide a larger intertidal zone if the southern breaches were larger allowing more exchange. The configuration of the CL scenario reduces its tidal exchange comparatively, as well as removing a portion of the tract, which lies in the appropriate elevation range. These two factors combine to limit the amount of intertidal habitat this scenario provides. The configuration of the SL scenario also reduces the extent of intertidal habitat, primarily due to the alignment of the setback levee, which isolates potential intertidal habitat from tidal inundation.

The extent of the supratidal zone does vary, however differences are small between scenarios. Major reductions are observed when portions of the tract in a suitable elevation range for this habitat zone are excluded from annual inundation, as in the SL scenario. Subtidal habitat is easily obtained, comprising a majority of the area in the scenarios that open the entire tract to tidal inundation (MBB, ETC and LR). Model simulation results show that the areal extent of the subtidal habitat type can be reduced through the careful placement of low levees isolating regions of the tract from continuous inundation (CL).

In restoration efforts in the North Delta there is a concern regarding the creation of subtidal/shallow water habitat. It is believed that this zone will provide more habitat for non native exotic plant and nekton species like *Egeria densa*, redear sunfish, largemouth bass, golden shiner, and inland silverside. Results from the spatial inundation analysis indicate that a majority of the subtidal zone in each of the scenarios will be between 0 and 0.5 m deep at MLLW. While permanent inundation at these depths would prevent the natural establishment of native marsh species including *Scirpus* spp. and *Typha* spp., recent research in the study area indicates that these species may be able to persist in the subtidal zone if planted (Jeff Hart, personal communication). If planting efforts were successful, established vegetation could enhance sedimentation of these subtidal zones, potentially providing enough accretion to move these regions into an intertidal zonation.

Model results suggest that restoring tidal freshwater marsh habitat within the MWT will have minimal impacts upon flood stages in a variety of flood magnitudes including rare, large events. Each scenario provides the potential for a mosaic of habitat types, as well as providing some flood mitigation benefit above or below the tract. Which scenario is the best depends on the objectives of the combined flood control and habitat enhancement effort. Not surprisingly, the optimum management configuration is different depending upon the desired result. Management decisions and further research regarding the benefit, or lack thereof in the creation of subtidal-shallow water habitat, are needed to determine whether it is necessary to partition the tract reducing the potential area of this habitat type.

In most scenarios considered, restoration and flood mitigation are shown to be compatible. Most scenarios evaluated in this study provided positive values for ecological and flood control benefits through the range of flood magnitudes investigated. Breach width, depth, and location will exert a large control upon the regional hydraulics, as well as the resulting inundation pattern upon the tract, and therefore the areal extent of the different habitat types. Furthermore, many factors in addition to the flooding frequency, will contribute to the development of the various habitat types in a restored MWT. These include sediment deposition and biogeomorphic evolution of the tract, seed sources of both native and exotic vegetation types, founder effects, and variations in hydrologic conditions and water resource facility management.

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