RESTORING KUNZ MARSH

A case history addressing marsh surface subsidence

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PROJECT SUMMARY:

To test active methods for adjusting marsh surface subsidence, four 0.7 hectare research "cells" were constructed in a subsided marsh in South Slough National Estuarine Research Reserve (South Slough NERR). The cells were filled with on-site dike material to high, middle, and low inter-tidal elevations. Filling and grading to a high-marsh elevation resulted in rapid colonization of emergent marsh vegetation but sacrificed the development of tidal channels. Manipulating the marsh surface to a low-marsh elevation resulted in slower colonization of emergent vegetation but allowed tidal channel development and provided more habitat for fish in the earliest stages of marsh recovery. Filling and grading to a middle-marsh elevation created conditions favorable for relatively rapid colonization of emergent marsh vegetation while allowing tidal channel development over time. Invertebrate communities developed most abundantly in the middle- and low-elevation research cells. Fill material consolidated as expected and did not become redistributed off-site. Reserve staff determined that manipulating marsh surface elevation is a viable method for accelerating the recovery of structure and functions in subsided salt marsh wetlands.

BACKGROUND

A key challenge for restoring some estuarine wetlands is adjusting for marsh surface subsidence. Subsidence has occurred in many marshes that were diked and converted to agricultural uses in the early twentieth century (e.g. Taylor 1983) (see sidebar). Removing or breaching dikes will restore tidal flooding to a marsh and ultimately revive the process of vertical accretion and the associated development of marsh plant communities and tidal channels. However, in many cases, subsidence has lowered marsh surfaces far below the elevation needed to support colonization of emergent vegetation (see Figure 1). Where the goal of restoration is to create a salt marsh, active methods can most effectively accelerate restoration (Cornu and Sadro 2002).

For example, long-term rates of vertical accretion for tidal marshes in the Pacific Northwest have been calculated to be only 2.4 to 4.8 mm per year (Thom 1992). At that rate, using passive restoration methods such as dike breaching, it would take between 20 and 40 years for marsh surface elevations at Kunz Marsh to reach a level that could support emergent vegetation and for tidal channels to develop. Until then, the site would remain an intertidal mud flat and provide valuable estuarine functions, but salt marsh functions would remain underrepresented in the estuarine system.

After analyzing the Reserve's Kunz Marsh, Reserve staff and the Winchester Tidelands Restoration Project (WTRP) Advisory Group (restoration specialists from academic, government, consulting, and non-profit organizations) determined that the site presented an ideal opportunity to test active restoration methods to address the issue of marsh surface subsidence.
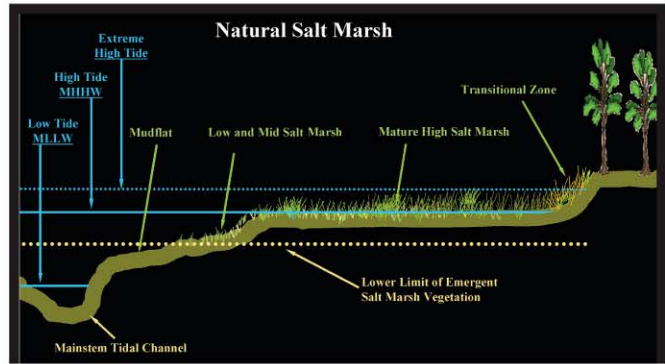
Figure 1. Comparison between natural salt marsh and subsided diked wetland, in profile.
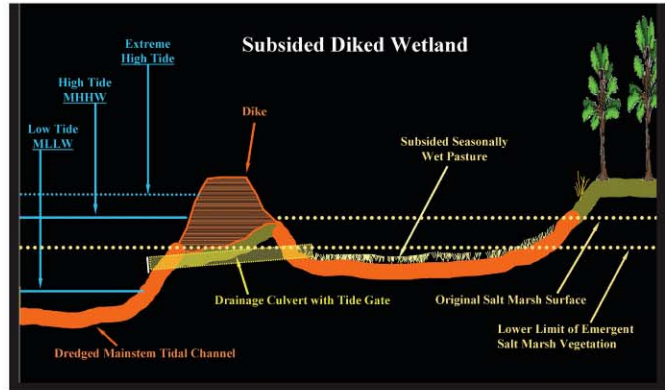
**Figure 2. Location of Kunz Marsh and South Slough.**
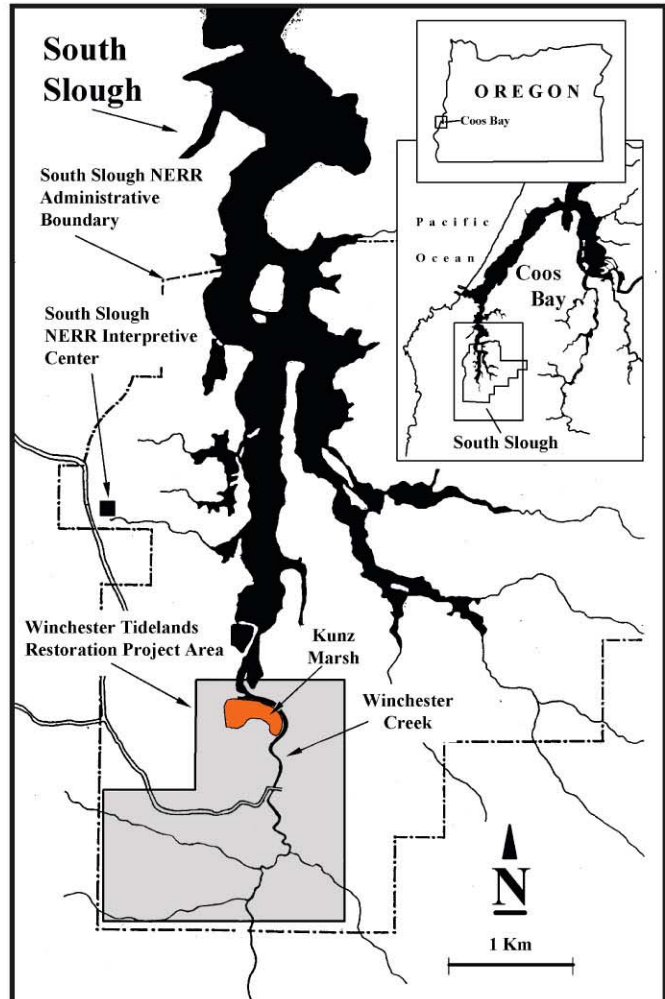
KUNZ MARSH

Kunz Marsh is located on the inside of a broad bend of the tidal portion of Winchester Creek (see Figures 2 and 3). Originally, the five-hectare site was a mature high marsh, but in the early 1900s, it was converted to cropland and pasture. A 1.5-m-tall dike was built to exclude tidal flooding. Meandering tidal channels were replaced by linear ditches that redirected fresh water from creeks and springs efficiently away from the marsh, especially during rainy winter months. A tide-gated culvert in the dike allowed fresh water from ditches to drain into Winchester Creek and prevented tide water

Figure 3. Kunz Marsh in 2003, with reference sites and location of developing tidal channels indicated.
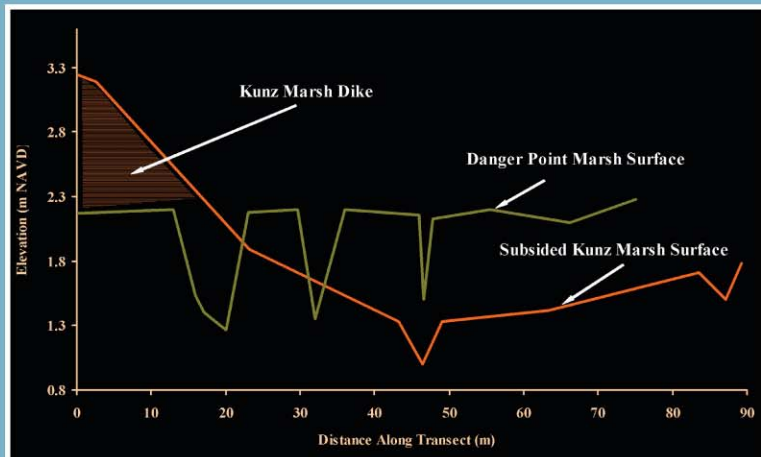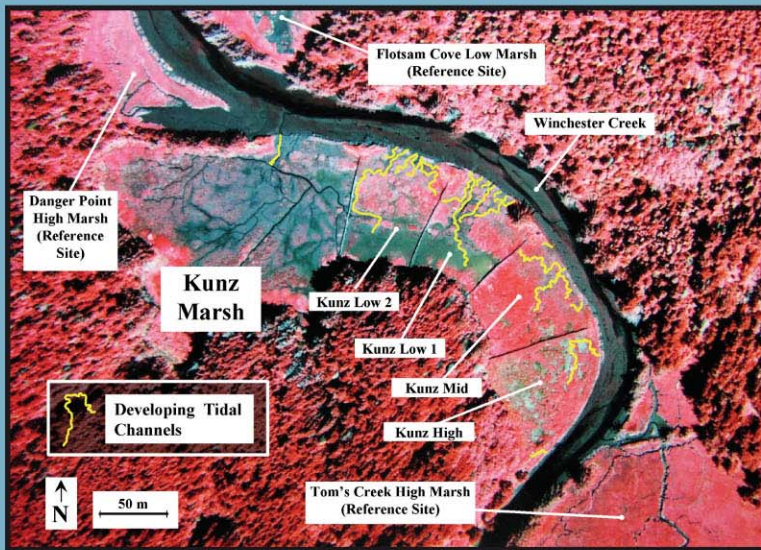
Figure 4. Kunz Marsh and Danger Point Marsh topographic profiles before restoration construction. Low points indicate channels or ditches.

SUBSIDENCE OF DIKED WETLANDS

Marsh surface subsidence has occurred in many estuarine wetlands that were diked and converted to agricultural uses in the early twentieth century. Because dikes excluded the natural process of tidal flooding from many marshes, they prevented the influx of sediment that had normally maintained salt marsh surface elevations.

When marshes behind the dikes dried out, their peat soils began to oxidize, decompose, and consolidate. Furthermore, the vigorous wetland vegetation that had once added organic material each year was replaced by pasture vegetation that was continuously removed by grazing and haying activities. Heavy livestock and farm machinery further compacted soils (Roman et al. 1984; Frenkel and Morlan 1991; Anisfeld et al. 1999; Weinstein and Weishar 2002). Over the course of many years, it is likely that all these factors contributed to marsh surface subsidence at Kunz Marsh.

from flowing into the marsh. Over many years, the Kunz Marsh surface had subsided to a level as much as 80 cm lower than an adjacent undiked marsh (Cornu and Sadro 2002) (see Figure 4).

RESTORATION PLANNING AND METHODS

With the help of the WTRP Advisory Group, Reserve staff designed an experiment to test active adjustment of marsh surface elevations in the subsided marsh. Results from active salt marsh restoration in San Francisco Bay had shown that emergent vegetation could be re-established at subsided sites by using dredge material to restore surface levels to mature high marsh elevations, equivalent to the mean higher high water (MHHW) tidal elevation (Williams and Florsheim 1994; Williams and Faber 2001; Williams et al. 2002). However, such filling precluded the natural formation of tidal channels, key structural elements in natural salt marshes.

To determine the most effective approach to accelerate development of both emergent plant communities and tidal channels by natural processes, Reserve staff designed an experiment to establish and monitor high, middle, and low intertidal marsh elevations in four 0.7-hectare research cells at the Kunz Marsh site.

During planning for restoration at Kunz Marsh, two near-by, relatively undisturbed mature high marshes at Tom's Creek and Danger Point were used as reference sites to identify specific marsh surface elevations, or design elevations, to be used in the various research cells at Kunz Marsh.

In 1995, the failing tide gate at the Kunz Marsh site was repaired to permit soils behind the dike to dry sufficiently to support earth-moving equipment. The following summer, construction began when an excavation contractor removed the top 15 to 30 cm of existing topsoil and vegetation from the marsh surface and stockpiled it in the corner of the site. This topsoil with its valuable organic matter was saved for later redistribution over the elevated marsh surface in each

cell. Approximately 10,000 cubic meters (13,000 cubic yards) of earth from the Kunz Marsh dike were then excavated and used to fill the marsh surface to desired design elevations in each research cell. A small portion of the dike at the northwestern corner of the site was left in place to prevent tidal erosion of the Danger Point Marsh just to the north.

Figure 5. Kunz Marsh in 1997, one year after project construction, with research cell and reference site locations indicated.

Each research cell was open to tidal flooding from Winchester Creek, but 1.8-m-tall geotextile fences built between them were intended to encourage independent hydrological development in each cell (see Figure 5). At the outset, the surface elevation of the subsided marsh was 1.4 m MLLW at its lowest point (all elevations refer to elevation above mean lower low water (MLLW)). Each cell was then filled and graded to a surface elevation within the local intertidal elevation range needed to support emergent

SALT MARSH AND TIDAL CHANNEL FORMATION AND FUNCTION

Salt marshes are naturally formed when tidal flats in relatively protected areas accumulate sediments through daily tidal flooding and gradually build to elevations that support the colonization of salt-tolerant vegetation. Sediments from upland and ocean sources and organic matter from decaying wetland vegetation continually build the marsh surface upward in a process known as vertical accretion (Kearney et al. 1994; Cahoon et al. 1995; Cornu and Sadro 2002). At the same time, deep tidal channels with vertical walls form as the salt marsh builds up around them and stabilizes channel banks.

Tidal channels connected to freshwater creeks and blind tidal channels (tidal channels with no connection to an in-flowing freshwater source) serve as important pathways for the import and export of organic and inorganic material to and from estuarine wetlands. These materials, including nutrients, detritus, seeds and other propagules, help sustain wetland plant and animal communities and contribute to the estuarine food web. Tidal channels also help build the marsh through vertical accretion and provide habitat structure and foraging access for benthic invertebrates and fish, including juvenile salmonids (Williams et al. 2002). The channels that are gradually forming in the Kunz Marsh research cells are blind tidal channels.

marsh vegetation as follows: the Kunz High cell was graded to a mature high marsh elevation (2.4 m MLLW); the Kunz Low 1 cell was graded to an elevation at the lower limit of emergent marsh vegetation (1.7 m MLLW); and the Kunz Mid cell was graded to a middle marsh elevation in between the others (2.0 m MLLW). The Kunz Low 2 cell was left ungraded at its existing low-marsh elevation as control site. A remaining two-hectare portion of the marsh was too wet to support heavy equipment needed to manipulate the marsh surface and was left as an example of passive restoration.

To address the anticipated compaction of the underlying marsh soils and the consolidation of the fill material, a soil engineer recommended filling the high and middle marsh cells 15 cm higher than the design elevations. Each cell, except for Kunz Low 2, was graded to a 200:1 slope—from the upland edge of the site down to the Winchester Creek channel edge—to replicate the average gradient of local salt marsh reference sites.

After the cells were filled and graded to design specifications, the topsoil removed from the original marsh surface was redistributed over each cell to add organic material and to provide a more-hospitable substrate for vegetation to colonize. Reserve staff planted no vegetation anticipating that nearby marshes would contribute sufficient plant propagules to initiate colonization.

Before excavating the dike, Reserve staff worked with the contractor to calculate the minimum dike height needed to prevent site flooding at the highest tide during the three-week project-construction period. Just enough dike material was left in place to exclude tidal flows until the filling and grading work was complete. However, they were concerned that the low-tide period would not be long enough to allow the contractor to remove the final portion of dike. The contractor solved the problem by finishing site filling with material dug from rectangular 6 x 9 x 4-m trenches excavated just behind the dike in each cell (see Figure 6). On the last day, the contractor was able to quickly dispose of the final portion of dike by filling these trenches. Working with the ebbing tide from the high-marsh cell to the lowest cells, the contractor removed the remaining dike material during a single morning low-tide cycle. Full tidal flooding was restored to Kunz Marsh in late August 1996.

MONITORING AND RESULTS

In the years following project construction, Reserve staff, contractors, collaborating agencies, and volunteers collected data at Kunz Marsh to monitor changes in marsh surface elevation, vegetation community development, tidal channel formation, relative abundance of invertebrates, and fish use. Data was also collected at reference sites.
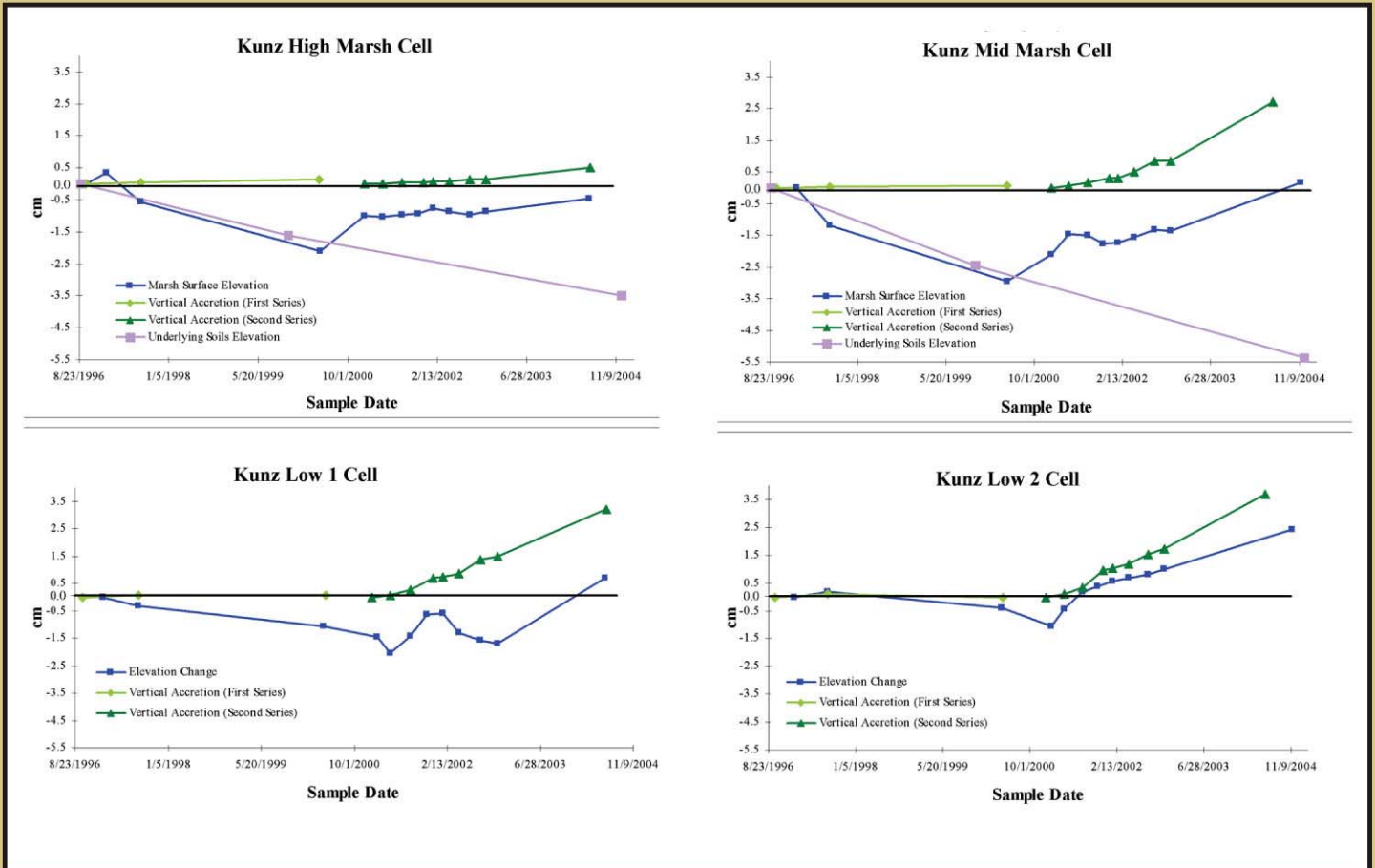
Marsh Surface Elevation

To determine change in marsh surface elevation in the research cells, Reserve staff measured vertical accretion, fill-material consolidation, and compression of the original marsh soils. By removing the dike, Reserve staff intended to restore the process of vertical accretion that would gradually raise the marsh's surface elevation. However, they also anticipated that fill-material consolidation and compression of underlying soils would have a temporary counteracting effect of lowering the Kunz Marsh surface elevation.

After three years (1996 to 1999), there was little natural build-up of the marsh surface, and vertical accretion rates remained very low in all Kunz cells (average rate of 0.19 cm/yr) compared to reference sites (0.70 cm/yr over five years of data

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collection). Reserve staff attributed low levels of vertical accretion primarily to the lack of vegetation cover at Kunz Marsh (Cornu and Sadro 2002). As plant communities became established in Kunz Marsh from 1999 to 2004, verti-cal accretion rates rose dramatically in all cells (averaging 0.73 cm/yr). However, vertical accretion rates were highly variable between the cells, ranging from 0.15 cm/yr in Kunz

High, to 0.78 cm/yr in Kunz Mid, to 0.93 cm/yr in Kunz Low 1 and 1.07 cm/yr in Kunz Low 2 (see Figure 7). At reference sites, vertical accretion rates averaged 0.58 cm/yr over 10 years of data collection.

As anticipated, marsh surface elevation dropped from 1998 to 1999 in the high and mid cells due to consolidation of fill material, compression of the original marsh soils, and shallow subsidence, a natural consolidation of the upper 5 to 10 meters of tidal marsh soil (Kaye and Barghoorn 1964; Cahoon et al. 1995; Cornu and Sadro 2002). However, between 2000 and 2004, marsh surface elevations increased at a rate that essentially mirrored vertical accretion rates. Vertical accretion and marsh surface elevation data suggest that fill-material consolidation and subsoil compression were

no longer active processes in the high and mid cells by early 2001. However, the rate of subsoil compression measured in these cells averaged -0.54 cm/yr from 1996 to 2004. One possible explanation is that the settlement monuments used to measure subsoil compression may be settling into the subsoil, causing erroneous measurements. Reserve staff are investigating this and other possible explanations.

At the time of construction, Reserve staff had concerns that the relatively loose fill material spread on the subsided marsh surface could become re-suspended by tidal action, move off-site, and smother eelgrass beds located on intertidal mudflats of Winchester Creek. In the years following project construction, they found that fill material did not become redistributed off-site.

An unanticipated off-site result was the presence of coliform bacteria detected in the estuary after dike removal at the Kunz Marsh. Elevated coliform bacteria counts were likely due to high tidal flows inundating the marsh, which had been heavily grazed by elk for decades. It was not possible to determine whether the bacteria were from animal or decaying-vegetation sources.

Vegetation

After project construction in 1996, there was no vegetation cover in the Kunz Marsh research cells, and no vegetation was planted. Reserve staff anticipated that natural recruitment of plant propagules from adjacent marshes would establish plant communities (see Figure 8). To determine how marsh surface elevation influenced vegetation colonization, Reserve staff annually collected plant abundance data along three permanent transects in each cell during late summer (July to September).

In the first three years following project construction (1996 to 1999), salt marsh plant communities developed faster in the high and mid cells than in the low cells (see Figure 9). In all cells, early salt-marsh colonizers dominated

Figure 8. Vegetation community development in the Kunz Marsh Mid cell, 1996 to 2002.

during this period. (Early salt-marsh colonizers are native and non-native species that quickly colonize bare soils, such as brass buttons (*Cotula coronopifolia*), toadrush (*Juncus bufonius*), orache (*Atriplex patula*), dwarf spikerush (*Eleocharis parvula*), and salt marsh sand-spurry (*Spergularia marina*)). In the high cell, residual pasture grasses, such as velvet grass (*Holcus lanatus*), initially grew with the early colonizers. By 1999, however, permanent salt marsh species were 66% more abundant in Kunz High than early colonizers or residual pasture grasses (Cornu and Sadro 2002). By 2004, they were 80% more abundant in Kunz High. (Permanent salt marsh species are native plants expected to persist in the salt marsh plant community over the long term, such as Lyngby's sedge (*Carex lyngbyei*), tufted hairgrass (*Deschampsia caespitosa*), bentgrass (*Agrostis spp.*), saltgrass (*Distichlis spicata*), and arrow-grass (*Triglochin maritimum*)).

In the mid and low cells, permanent species took longer to become established, and early colonizers continued to persist, still averaging 59% of total abundance in 1999 (Cornu and Sadro 2002). By 2004, however, permanent species were an average of 80% more abundant than early colonizers in these cells, and residual pasture grasses were virtually absent in all cells.

Patterns of emergent vegetation abundance were positively correlated with differences in marsh surface elevation through 1999 (Cornu and Sadro 2002). In all cells, salt-tolerant, early colonizing species appeared to facilitate the establishment of permanent salt marsh species (Bertness 1991) by varying degrees depending on marsh surface elevations and their associated tidal inundation periods. From 2000 to 2004, however, those patterns changed as plant communities in all cells, particularly the mid and low cells, became increasingly similar. Vegetation abundance patterns at the reference sites were strikingly different from those at the Kunz Marsh research cells, reflecting the relative stability of the mature plant communities (see Figure 10).

Kunz Marsh Mid Cell - 1996   **Kunz Marsh Mid Cell - 1999**   **Kunz Marsh Mid Cell - 2002**
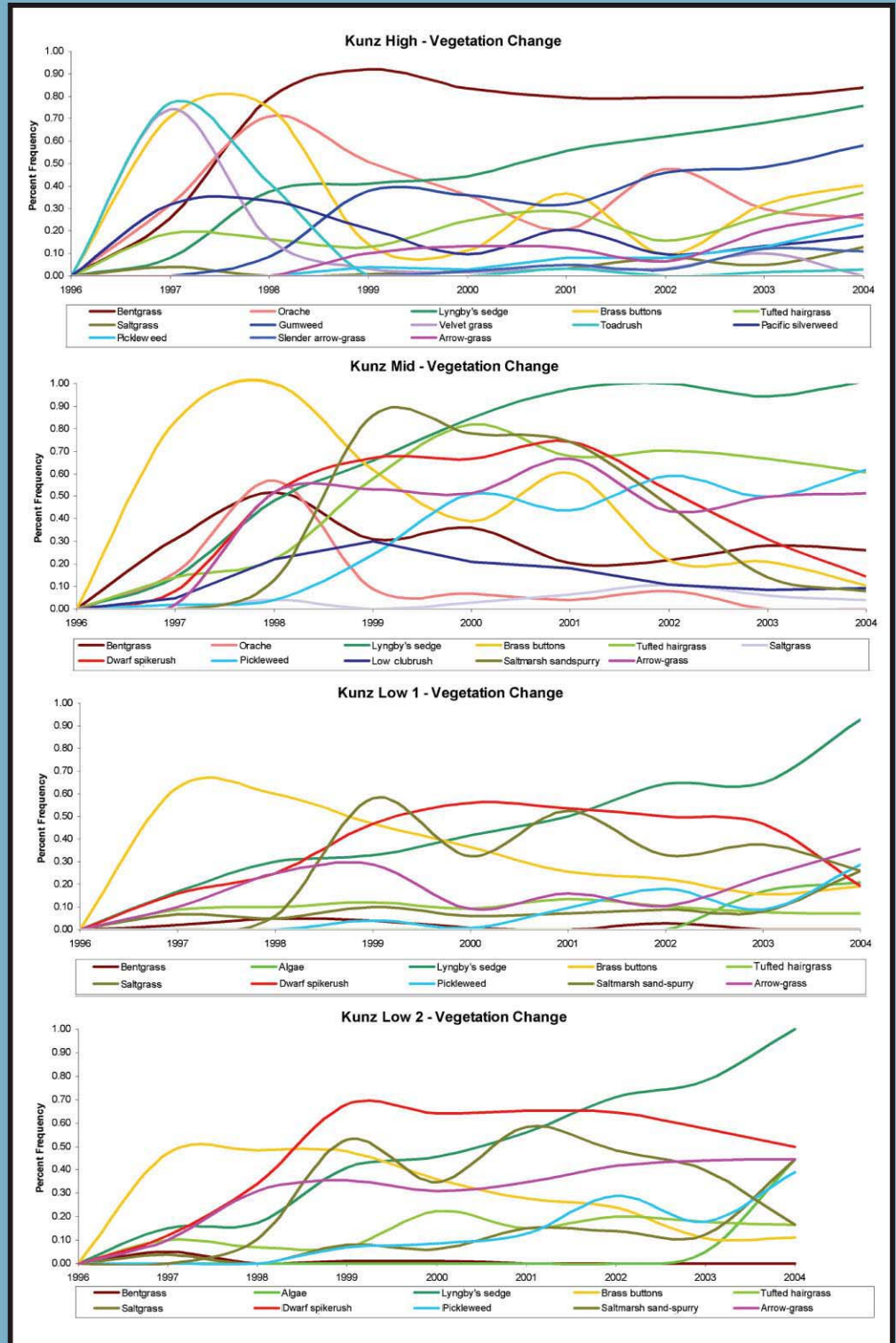
Tidal Channel Formation

To monitor tidal channel development in the Kunz cells, Reserve staff measured several channel attributes: length, width (at channel top and bottom) and depth at the mouth and at an approximate midsection, and sinuosity ratio. Typically in natural estuarine systems, blind tidal channels evolve from meandering rivulets that form on low intertidal mudflats as tidal water drains from the marsh surface. As sediments accumulate and vegetation colonizes the mudflat, a vegetated marsh builds up around the emerging channels (Coats 1995). Accordingly, Reserve staff expected that tidal channels would eventually develop most fully in the low cells but hardly at all in the high cell.

By 1999, Reserve staff found that seven principal tidal channels had begun to form: two in the high cell, one in the mid cell, and two each in the Low 1 and Low 2 cells. By 2004, 16 additional channels had begun to develop; most of these were more fully formed than channels observed in 1999 (see Figure 11). In the high cell, however, the small channels remained poorly developed. Larger channels developed in the mid and low cells, but some channel formation in the low cells was related to factors beyond project design.

The Kunz Low 2 cell was not graded to a designed slope. Originally, this cell was intended to be a control site altered only as necessary to fill the ditch running through its center. However, in the course of filling the ditch, the contractor had to temporarily place fill on the near-channel portion of the cell to provide access for equipment, and the slope of the

Figure 9. Percent frequency of the most abundant vegetation species in the Kunz Marsh research cells, 1997 to 2004.

cell was inadvertently changed. This has significantly slowed the formation of tidal channels in the Low 2 cell compared with the Mid and Low 1 cells.

In the Kunz Low 1 cell, another factor fostered development of larger tidal channels. A small freshwater stream that flowed into the cell for a year after project construction eroded several channels. So far, the size and shape of the tidal channels that are evolving in the Low 1 cell have been influenced more by the erosional forces of this freshwater stream than by the tidal processes. To eliminate the counteracting influence of the stream and re-establish consistency with the other research cells, a small channel was dug in the project's second year to redirect the stream flow into Winchester Creek through the passive restoration cell.

After eight years, results show that tidal channel development at Kunz Marsh has been influenced by marsh surface elevation except where surface gradient or stream flows beyond the scope of experimental conditions exerted an influence. However, channel size was not strongly correlated with surface elevation (Cornu and Sadro 2002). Reserve staff expect that tidal channels will continue to develop in the mid and lower cells through long-term vertical accretion and erosional processes.

Fish Use

To determine how marsh surface elevation influenced fish use, Reserve staff monitored fish density and species composition in each of the research cells once monthly, over a five-month period (November 1998 to March 1999), two years after project construction. A total of 4,589 fish representing eight species were caught in the Kunz Marsh cells. Topsmelt (*Atherinops affinis*) and staghorn sculpin (*Leptocottus armatus*) comprised over 98.3% of the total catch for all cells (see Figure 12).

As anticipated, there were greater numbers of fish (83%) and a greater diversity of species (7 out of 8) in the low-elevation cells because fish simply had greater access to these cells, which were inundated longer with greater volumes of water at
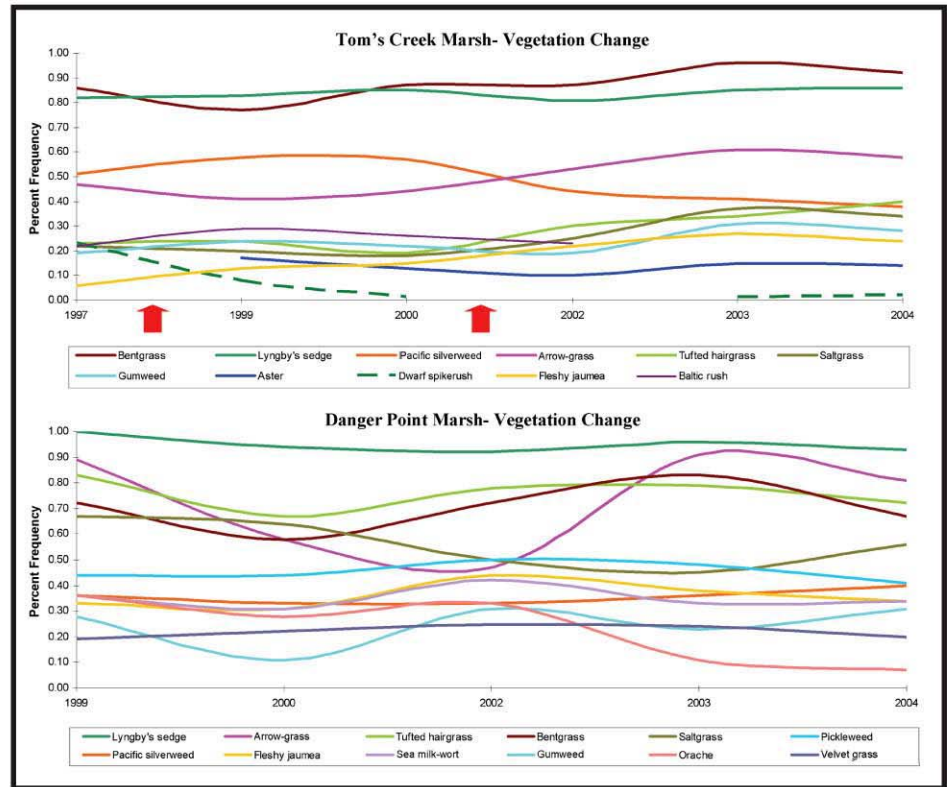
Figure 10. Percent frequency of the most abundant vegetation species at the Tom's Creek and Danger Point Marsh reference sites, 1997 to 2004 (arrows indicate years when data was not collected).

Figure 11. Tidal channel attributes in Kunz Marsh research cells in 2004. Measurements from 2000 are in parentheses for comparison.

Cell	Channel	Length (m)	Mouth Width/ Depth (cm)	Mouth Area (m^2)	Sinuosity Ratio	Connections with Lower Order Channels
Kunz High	North	7 (65)	n/a	n/a	n/a (2.27)	0 (2)
	South	9 (15)	n/a	n/a	n/a (1.43)	0 (0)
Kunz Mid*	Main	30.5	105/65 (80/25)	0.34 (0.13)	1.5	2
	Trib.1	45 (50)	57/36	0.17	1.2 (1.4)	2 (2)
	Trib.2	15.0	37/30	0.08	1.2	1
	Tiny W.	1.5	37/22	0.06	1.2	1
	TinyE.	2.5	52/57	0.23	1.1	1
Kunz Low 1	West 1	101 (75)	245/60 (210/95)	1.44 (1.6)	1.2 (1.2)	9 (0)
	Trib	33.6	116/41	0.29	1.4	5
	West 2	2.9	65/30	0.14	1.3	0
	West 3	44 (30)	195/67 (290/85)	1.12 (1.24)	1.1 (1.0)	5 (1)
	East 1	3.7	63/23	0.11	1.5	1
	East 2	1.0	57/17	0.06	1.0	0
	East 3	4.5	70/17	0.09	1.2	1
	East 4	14.6	80/44	0.26	1.2	4
Kunz Low 2	West 1	3.5	66/17	0.07	1.1	0
	West 2	61.5 (28)	110/29 (90/10)	0.27 (0.09)	1.2 (1.3)	6 (3)
	West 3	104 (88)	83/35 (95/21)	0.19 (0.13)	1.7 (1.3)	6 (12)
	West 4	4.5	180/30	0.41	1.3	0
	Tiny 5	0.7	19/5	0.09	1.0	0
	East	26.0	54/32	0.13	1.2	0
	N.East	6.0	53/30	0.13	1.4	1
	South	4.9	54/17	0.08	1.1	1

Channels existing in 2000 are indicated in **bold**
Channels dimensions in 2000 are indicated in (parentheses)
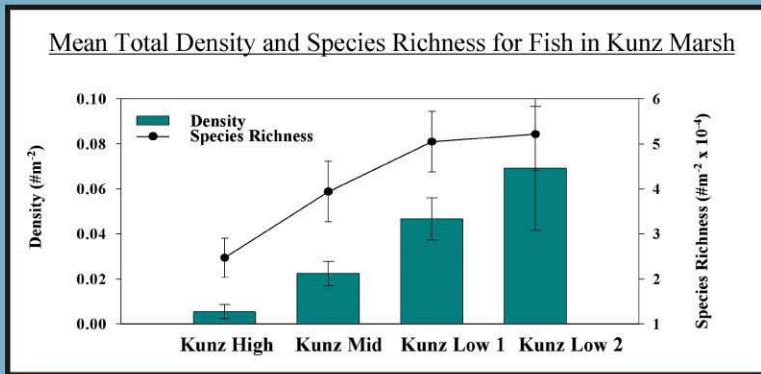* In 2000, there was only one channel in Kunz Mid. By 2004, that channel turned into the current Trib. 1.

Mean Total Density and Species Richness for Fish in Kunz Marsh
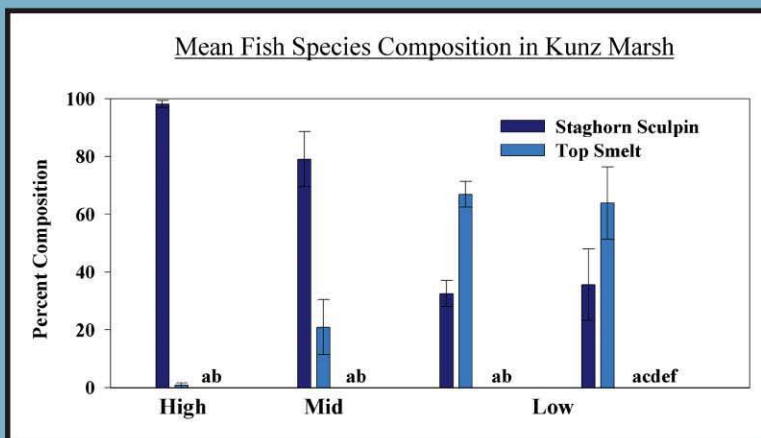
Mean Fish Species Composition in Kunz Marsh

Coleoptera (beetles) when compared with the high and mid cells (see Figure 14). These results were generally matched at corresponding reference sites: invertebrate abundance was greater at the Flotsam Cove low-marsh reference site than at the Tom's Creek high-marsh reference site. However, the Danger Point high-marsh reference site was a notable exception, with greater fallout-trap abundances all three years compared with all other sites. Reserve staff are investigating possible reasons for this difference.

In all three years sampled, sediment core data showed little difference in total benthic invertebrate abundance in the mid and low cells, where various amphipods, isopods, polycheate worms, snails, and some kinds of fly larvae were common. The high cell had lower benthic invertebrate abundance than all other cells during the same period. Low abundance of benthic invertebrates was also recorded at the low-elevation Flotsam Cove reference site, but both high-elevation reference sites (Danger Point and Tom's Creek) appeared to exhibit greater benthic invertebrate abundances than the Kunz High cell (see Figure 15). In addition, there appears to be a trend of increasing total abundance of benthic invertebrates at all Kunz cells, except the Kunz High cell. In contrast, the reference sites show relatively stable benthic-invertebrate-abundance levels.

high tides. Topsmelt accounted for 64% to 67% of the total catch in the low cells, while coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Oncorhynchus clarki clarki*) each accounted for less than 1% (Cornu and Sadro 2002) (see Figure 13).

Reserve staff found a significant inverse relationship between marsh elevation and the distribution and abundance of fish. However, it remains unclear whether fish selectively entered the low-marsh cells or were passively flooded into those areas with a high tidal volume. There were no fish data available from local reference sites.

Invertebrate Community Development

Invertebrates, many of which are important prey resources for juvenile salmonids and other estuarine fish, were sampled in the Kunz cells and reference sites, including a new low-marsh reference site, Flotsam Cove, in May of 2000, 2001 and 2002. Samples from a total of 36 fallout traps and 126 sediment cores were collected and analyzed.

From 2000 to 2001, Reserve staff found little difference in total invertebrate abundance from fallout traps among the Kunz cells, where *Dipterans* (flies) from all life stages dominated. However, by 2002 total invertebrate abundance was greater in the Low 1 and 2 cells, particularly for adult

There appear to be potential links between marsh elevation (tidal inundation period) and invertebrate community abundance, however the links observed are likely complicated by other factors including marsh structure and age. The apparent trend of increasing benthic invertebrate abundance in the Kunz mid and low cells may reflect the rapidly changing conditions associated with recovering estuarine marshes (Gray et al 2002). For example, tidal channel development in the Kunz mid and low cells may have created new niches for invertebrates while in the Kunz High cell and the mature high-marsh reference sites, habitat change occured less fre-

Total Invertebrate Abundance from Fallout Traps

Total Average Abundance of Benthic Invertebrates
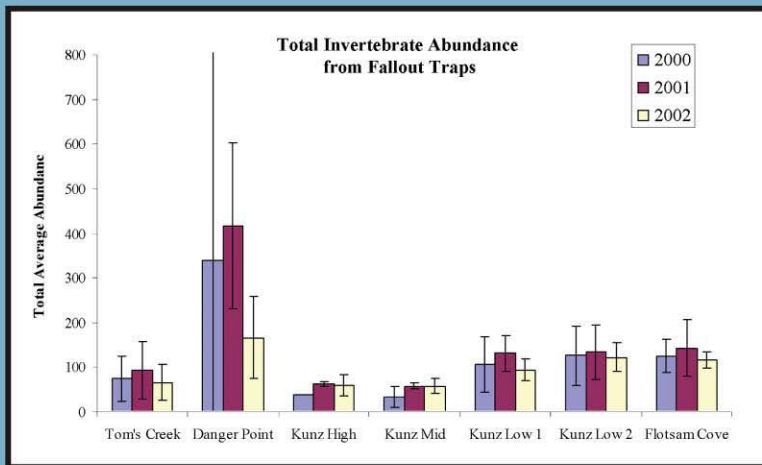
Figure 14. Total invertebrate abundance from fallout traps at Kunz Marsh and reference sites. Error bars are standard deviation and represent variation between replicate traps.
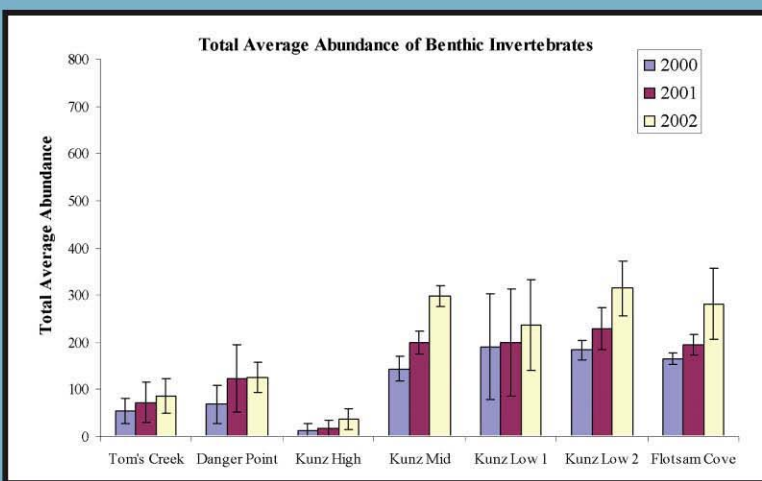
Figure 15. Total benthic invertebrate abundance from sediment cores in Kunz Marsh and reference sites. Error bars are standard deviation and represent variation between replicate cores.

quently offering fewer opportunities for invertebrate recruitment. The low-marsh reference site shows a similar though less pronounced trend of increasing benthic invertebrate abundance. Reserve staff will continue to collect invertebrate data at these sites to track the response of invertebrates to habitat development in the Kunz Marsh research cells and to document natural variability of invertebrate communities at the reference sites.

LESSONS LEARNED

Through restoration experiments at Kunz Marsh, Reserve staff learned that actively filling and grading the subsided marsh surface to particular elevations resulted in the development of vegetation communities and tidal channel formation at different rates. Filling and grading to a mature-high-marsh elevation resulted in rapid colonization of vegetation but sacrificed the formation of tidal channels and habitat to support abundant invertebrate communities. Manipulating the marsh surface to a low-marsh elevation resulted in slower initial development of plant communities but allowed channel development and provided more fish habitat in the earliest stages of marsh recovery. Filling and grading to a middle-marsh eleva-

tion created conditions favorable for colonization of emergent vegetation while also allowing tidal channel development over time.

Except in cases where there are unlimited quantities of dredged material, it may be impractical to adjust for subsidence for an entire marsh because there will rarely be enough dike material available. However, understanding the factors that influence how marshes form, develop, and reach dynamic equilibrium, can help project planners choose the best strategy for restoration. By re-establishing the key physical elements, such as marsh surface elevation and tidal flooding, project planners can set the stage and then allow site recovery to proceed on its own. This is called "self-design" (Mitsch 2000). The self-design approach has the dual benefits of permitting development of more-naturally formed structures and also of being more cost effective because natural processes rather than earthmoving equipment do most of the work.

Results at Kunz Marsh, for example, suggest that on-site dike material could be used to build up a subsided, estuarine-wetland site at its upland edge as much as the quantity of dike material would allow. More research is needed to determine whether natural processes would then continue the work of building the marsh out to the main tidal channel. Or if the primary restoration goal is accelerating development of fish habitat, filling a larger portion of marsh to the low-marsh elevation could be the most effective strategy.

Experience at Kunz Marsh suggests that, when possible, complete dike removal should be the preferred method for restoring tidal flooding to estuarine wetland sites. This method allows recovering marshes to receive the full contribution of nutrients from upland, estuarine, and ocean sources, thereby hastening the development of marsh structures and functions. Through time, complete dike removal will also allow the estuary to receive the full benefit of the detritus and nutrients contributed by the developing marshes. Results of the Kunz Marsh Restoration Project indicate that complete dike removal, filling ditches, and adjusting for marsh surface subsidence can be effectively accomplished together.

GLOSSARY

benthic invertebrates: cold-blooded animals without backbones that live in and on sediments associated with bodies of water (estuaries, oceans, lakes, streams, etc.), including amphipods (*Corophium spp.*), isopods (*Gnorimosphaeroma spp.*), segmented worms (*Nereis spp.*), insect larvae and pupae, and others

blind tidal channels: tidal channels not associated with an inflowing freshwater stream

emergent vegetation: rooted plants that can tolerate some inundation by water and that extend photosynthetic parts above the water surface for at least part of the year; they are intolerant of complete inundation over prolonged periods

Mean Lower Low Water (MLLW): the average height of the lower low tides observed over a specific time interval; used as a standard elevation benchmark in estuarine research

low marsh: a wetland ecosystem characterized by twice-daily inundation of high tides and by salt-tolerant emergent vegetation

marsh surface subsidence: the lowering of marsh surface elevation over time due to soil oxidation and consolidation, physical compaction, and the absence of tide-borne sediment deposition in diked wetlands

mature high marsh: a wetland ecosystem influenced by a marsh surface elevation at approximately MHHW that is inundated by only the most extreme high tides and characterized by salt-tolerant emergent vegetation

Mean Higher High Water (MHHW): The average height of the higher high tides observed over a specific time interval; used as a standard reference to gauge extent of tidal influence

middle marsh: a wetland ecosystem characterized by inundation by the higher range of tides and by salt-tolerant vegetation

propagule: a dispersal stage of a plant or animal such as fertilized eggs, larvae, seeds, or rhizomes, that propagates a new organism

reference site: an undisturbed or minimally disturbed landscape that exhibits the structure and functions characteristic of a natural ecosystem and serves as a model for planning a restoration project

sinuosity ratio: a measure of the amount of curvature in a stream channel, calculated by dividing the meandering distance a stream travels by the straight line distance it covers

vertical accretion: increase in marsh surface elevation caused by addition of sediments and organic materials

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