



## COASTAL MARSH RESTORATION CHALLENGES: AN INTER-CONTINENTAL COMPARISON

Google Earth image of the Lake Superior National Estuarine Research Reserve

Coastal wetlands develop at the mouths of rivers where upstream-downstream gradients create estuaries. While salt, and especially sodium chloride (NaCl), is the usual chemical gradient across estuarine wetlands, other solutes can grade downstream toward lakes, creating freshwater estuaries. One in Wisconsin, the St. Louis Estuary entering Lake Superior, is a National Estuarine Research Reserve.

Estuarine wetlands respond to changes in their chemical gradients when there are changes in either land uses or rainfall patterns. A common change is for more water to flow downstream. However, during droughts, less water flows downstream and water near the mouth, which is normally fresh, can accumulate salts. Salt concentrations are extremely important to biological communities, because even small amounts of NaCl can be toxic to sensitive species. Salinization is a major challenge to restoration efforts, because salt inflows are controlled by upstream watersheds, not local restoration sites.

Nowhere are the effects of shifting chemical conditions more apparent than in intertidal marshes (those regularly flushed with seawater) in regions with Mediterranean-type climate (cool, moist winters and warm, dry summers).

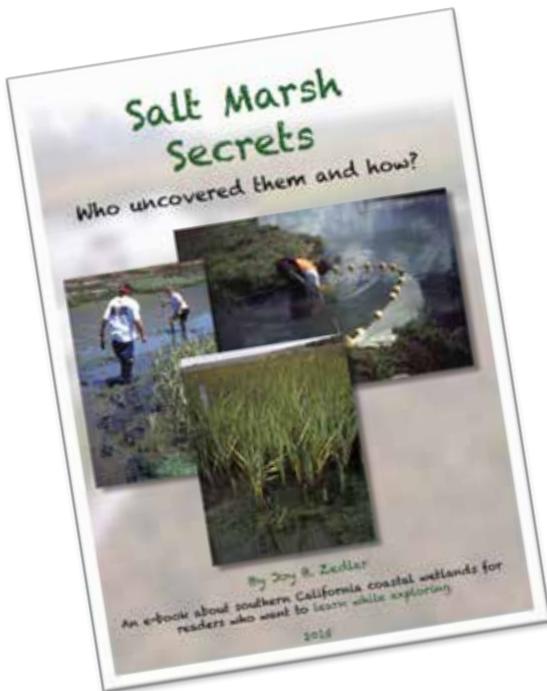
My co-authors and I invite you on a virtual trip to coastal wetlands that offer *lessons* for coastal marshes here in Wisconsin--along the Great Lakes and even along our own Lake Wingra.

### Mediterranean-type salt marshes

Salt marshes are distinguished by their high concentrations of salt; those along oceans have highly predictable inundation regimes due to daily tides. From the lowest elevation of a salt marsh to its upland boundary, tidal water depths fluctuate predictably. Rare exceptions are high waters during river floods and sea storms. Cool-season rainfall and long warm summers shape the Mediterranean-type vegetation, but the effect of this unique climate is not the same for terrestrial and intertidal habitats. In uplands, the native vegetation grows and reproduces in the cool season when it rains. In intertidal wetlands, however, plants have access to tidewater year-round; the plants just have to tolerate seawater (~3.4% salts, mostly NaCl). Species that dominate Mediterranean-type salt marshes typically tolerate hypersaline soil (4.0-4.5%). Such halophytes transpire year round, so their roots continuously draw water and concentrate soil salts. Most

are perennial evergreen succulents. Because they tolerate tidal wetting, they can grow best in the warm season, rather than the cool, rainy season.

The upper limit of regular tidal influence is easy to distinguish in summer—the marsh vegetation is primarily green, while uplands accumulate brown biomass of dead annuals and dormant perennials. The benefits of a long warm season outweigh the costs of overcoming the toxic and osmotic challenges of tolerating salt. Annual species that cannot tolerate high salinities dodge the salts by germinating after the first rains and completing their life cycle in short order, before rainfall ceases and soil salinities rise again. In Southern California, one annual species, the endangered salt marsh bird's beak (*Cordylanthus maritimus maritimus*, a hemiparasite), stretches its growing season by tapping native perennial plant roots for moisture and nutrients, thus enabling them to flower and set seed in summer. Photos are in my online eBook at [trnerr.org/SaltMarshSecrets](http://trnerr.org/SaltMarshSecrets) (downloads are free).



In Southern California, the highest tides occur in January and June, and minimum amplitudes are in March and September, at the equinox. In the upper marsh, gaps in the canopy allow the dark organic soil to heat up in summer, when soil water evaporates directly, leaving a salt crust behind. There, the wetland-upland boundary (ecotone) supports boxthorn (*Lycium californicum*), which shares characteristics of both the saline and nonsaline

realms—it is summer deciduous like the upland coastal sage scrub *and* salt tolerant like the high intertidal marsh, at least as an adult. This subshrub takes advantage of a narrow ecotone that is too dry for most halophytes and too saline for most salt-intolerant plants. Not surprisingly, ecotone soil salinity is dynamic, determined by salt inflows with sea storms and salt dilution with rainfall or flooding. Seedlings do not establish very often. Matt James' experiments with young plants indicated that the soil at the ecotone is usually not wet long enough to leach out the salts plus trigger seed germination and then sustain growth of seedling roots down to the water table. The same salts that control germination in an ecotone species also limit the downslope occurrence of coastal sage scrub perennials (e.g. *Eriogonum fasciculatum*, *Isocoma veneta*). Moving downslope, the high marsh supports about 16 perennial halophytes and 5-10 native annual species, plus many exotic annuals. Another 8-10 halophytes are common on the marsh plain (20-30 cm lower in elevation), where frequent tides keep the soil wet and shallow depressions waterlogged.

Two lessons for restoration are that *soil salts determine upland-wetland vegetation boundaries* and, together, *water levels and salt content determine salt marsh species composition*.

## Restoration challenges

Whole-system biodiversity can decline rapidly following a catastrophic disturbance, such as mouth closure that leads to extreme hypersalinity or prolonged river flooding and hyposalinity (salt dilution). Some losses are permanent (sand dollars never recovered after the 1978 river flood at Tijuana Estuary). Mortality occurs much more readily than reestablishment. For a plant or animal to recolonize a salt marsh, propagules must be available, and the salinity and water requirements must be met (often more strict than what adults can tolerate). Where cordgrass (*Spartina foliosa*) dies back due to hypersalinity, the more salt-tolerant pickleweed (*Sarcocornia pacifica*) expands to take its space, reducing the ability of cordgrass to reestablish. Thus, *it is better to prevent species loss than to allow damages and attempt to reintroduce species*.

Plants of the salt marsh, brackish marsh and wetland-upland ecotone all seem to germinate and grow best with reduced salinity; the differences are the degrees of tolerance. In Southern California, the halophytes that grow on the marsh plain can germinate in full seawater, while several plants that occur in the high marsh or in

brackish areas require salinities under 2‰ or 1‰. Where studied, adult plants tolerate higher salinities than their seeds and seedlings. *The establishment step appears to determine distributions, since halophytes can persist in areas that are no longer suitable for their establishment.*

The need for lowered salinity and saturated moisture to restore salt marsh native species has *implications for restoration*. (1) Restoration sites that are extremely hypersaline will need leaching, which is difficult, especially in clayey soils. (2) Reference sites with mature vegetation will not necessarily reveal conditions needed for vegetation establishment. (3) Simultaneous measurements of abiotic and biotic variables are needed for restoration and reference sites. Old data might not provide a reasonable target for newly planted vegetation; e.g., cordgrass produced 40% more biomass above ground in a flood year than in nonflood years. (4) Invasive species also establish well with lowered salinity, so restoration plantings might be threatened by aggressive competitors, at least until salinities can be elevated (after native halophytes are well established).

#### Four restoration cases on three continents

Case studies from southwestern North America, South Africa, and southwestern Australia suggest that Mediterranean-type salt marshes are not easily restored. What can be done to sustain biodiversity where salts vary in response to land uses and climate change?

In Southern California, urbanization and agriculture have diminished the area and quality of coastal wetlands. The area available for salt marshes was never large, owing to the mountainous watersheds and narrow continental shelf. Once settled, 90% of the coastal wetland area was lost to sedimentation, filling and dredging. Today, most wetland remnants are in public ownership and filling is regulated, but sedimentation rates are still a chief concern: With too little inflowing sediment, salt marshes will be inundated by rising sea levels. Conversely, when too much sediment accumulates in an estuary, there is insufficient tidal energy to keep the ocean inlet open. With sand accumulation and tidal closure, a saline coastal wetland can become brackish if freshwater becomes impounded, or hypersaline if impounded water evaporates. *Salinity depends on conditions that both precede and follow inlet closure*. In either case, plant and animal populations undergo rapid declines. *Marshes that experience more or longer nontidal episodes have fewer native species than those with continuous tidal influence.*

#### Tijuana Estuary

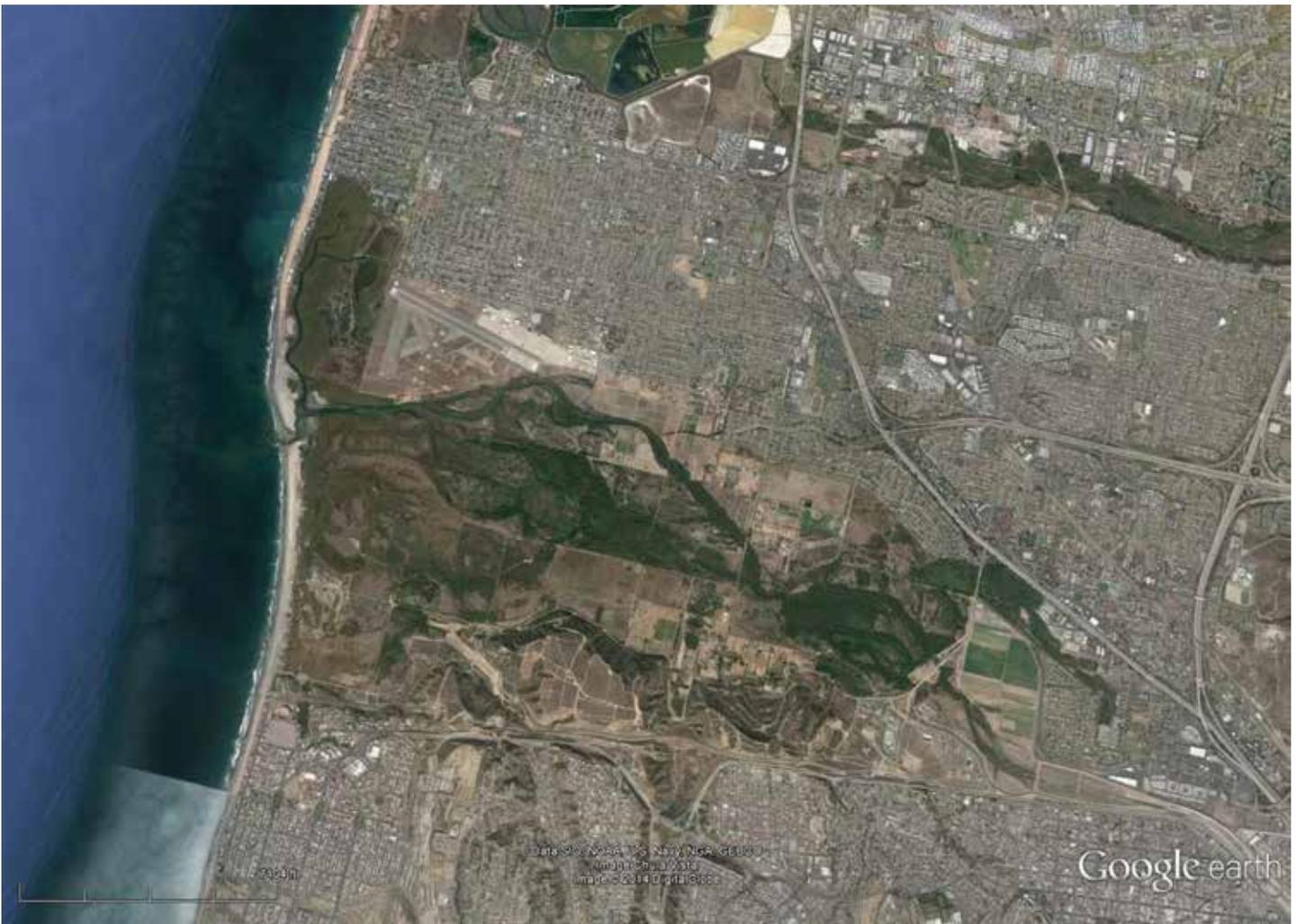
Southern California, 32°34'N, 117°7'W, San Diego County, California.

This National Estuarine Research Reserve includes 1024 ha of protected land, but only about 200 ha of fully tidal salt marsh. Three-fourths of its ~5000-km<sup>2</sup> watershed lies in Mexico, although the entire estuary is within the United States. The main damage to this estuary has been and continues to be sedimentation from a watershed that is highly erodible and subject to catastrophic floods. In addition, occasional sea storms wash over the human-denuded dunes, pushing sandy sediments into the adjacent tidal channels.

In 1984, the ocean inlet closed to tidal flushing and remained nontidal until a major dredging program cleared sand from the main tidal channel and reopened the mouth 8 months later. The impact of long-term closure during a drought year was measured as extreme hypersalinity (>6‰ in the water column and >10‰ in the marsh soil), drought (cracked bottoms of former tidal creeks by October 1984), widespread plant mortality, and declining animal populations (near-total mortality of surface-dwelling snails and extirpation of an endangered rail, *Longirostris obsoletus obsoletus*). Pickleweed became more abundant during closure, while cordgrass declined (as did the short-lived *Suaeda esteroa* and *Salicornia bigelovii*). Cordgrass gradually regained its pre-closure distribution, but the seed banks of the two short-lived species were depleted and have not fully recovered, despite recent decades with good tidal flow. The rail population rebounded, in part due to rearing and translocating chicks from nearby marshes.

**Restoring Tijuana Estuary.** Recommendations to restore lost salt marsh area date to the 1970s, but it was not until 1991 that a comprehensive plan was approved. The first site (0.7 ha) was excavated in 1997, and the second (8 ha) was added in 2000. These were small but costly beginnings (\$3.1 million to excavate and remove about 200,000 m<sup>3</sup> of sediments from the 8-ha site). A recent plan to excavate and restore tidal flows to 200 ha remains to be funded.

Several lessons were learned from restoring the first sites as large field experiments. The first site, called the Tidal Linkage, is a channel and narrow marsh plain that was excavated from disturbed upland. It connects a natural tidal creek to a tidal mudflat that was once a sewage oxidation pond for the adjacent City of Imperial Beach.



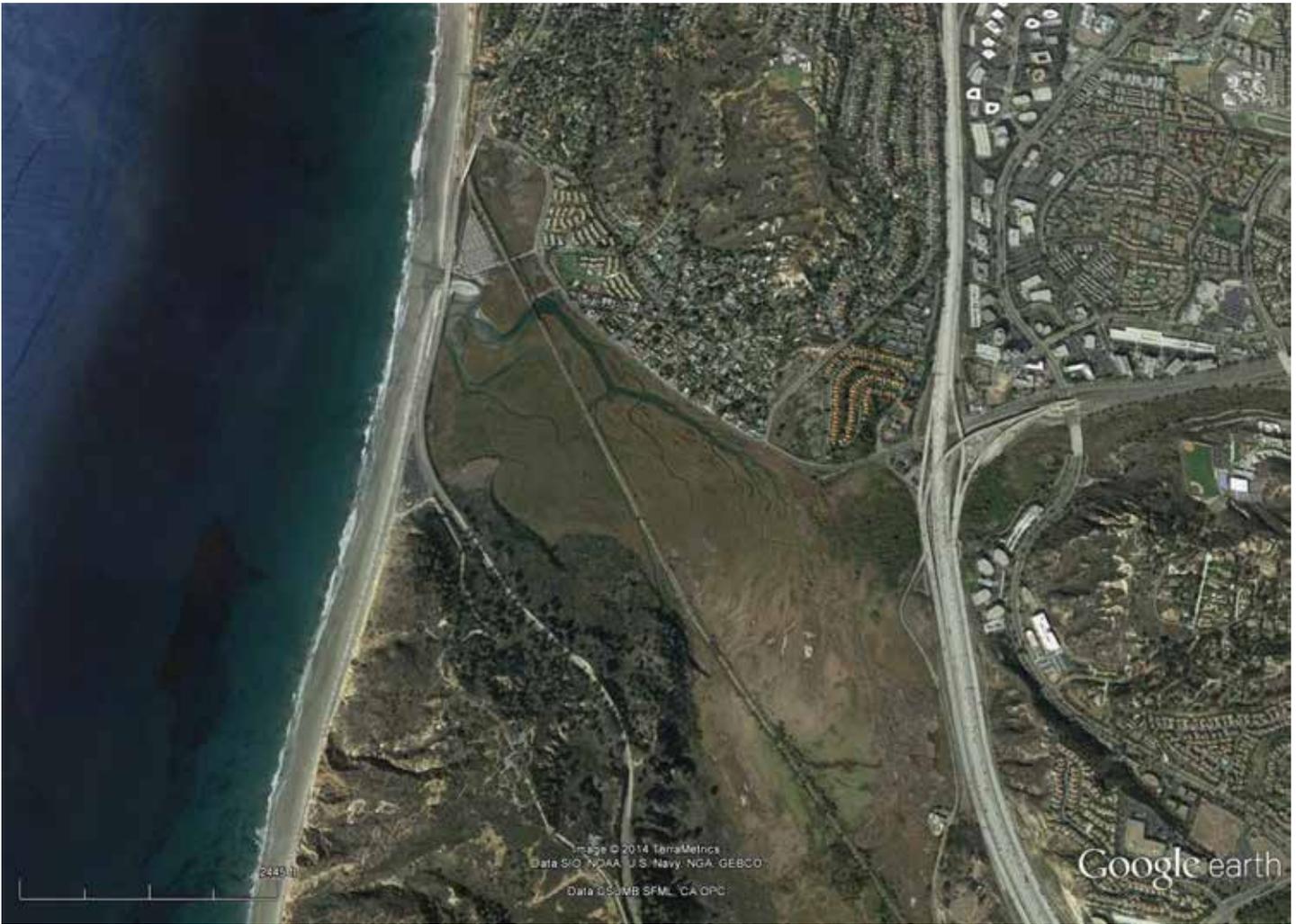
Google Earth image of the Tijuana Estuary

Our field experiment tested marsh-plain planting regimes in 87 experiment plots, each 2x2m (see eBook). We compared the structure and functioning of 8 individual species, as well as 15 trios and 15 sextets. We learned that *it was unnecessary to plant pickleweed; that the two short-lived species can self-restore where there are adequate seed sources, and that the five marsh-plain species must be planted*, even next to a natural marsh with access to dispersal via animals, water and wind.

We also learned to *expect surprises*. A hard pan (a -10-cm-thick layer of cemented coarse sand) was encountered at the desired marsh-plain elevation. For the experimental half of the site, we had a bulldozer break up the hard pan and incorporate fine sediments from the former sewage lagoon. Another surprise followed the planting of seedlings--an algal bloom covered the soil and attracted about 100 coots (*Fulica americana*) to graze while trampling our planted seedlings. Still, by year

2, plant cover was nearly 100%, and all 8 species were present. The site served science well, by supporting studies of canopy architecture by Georgeann Keer, seedling establishment by Roberto Lindig-Cisneros, nitrogen accumulation by John Callaway and Gary Sullivan, and long-term loss of “diversity effects” by James Doherty.

The second site is the Model Marsh, which tested the importance of including tidal creeks and soil amendments, as well as planting densities. Three areas (each about 1 ha) have tidal creek networks and three are flat marsh plains. The creeks supported fish use and fish access to the marsh plain where pools became feeding oases, documented by Dan Larkin and Janelle West. Clustered plantings and plants with amended substrates outperformed alternative treatments. *Sedimentation remained a threat* to the Model Marsh from upstream watershed in Mexico, where sediment control practices are not in effect. So, the California State Coastal Conservancy



Google Earth image of Los Peñasquitos Lagoon

converted Goat Canyon into dual sediment-control basins to settle inflowing sand and silt.

Our use of sites for experiments (Adaptive Restoration) led to a Handbook for Restoring Tidal Marshes, which is used throughout the region to design salt marsh restoration. The cooperation between managers, funding agencies, and researchers is a key feature of restoration at this National Estuarine Research Reserve.

## Los Peñasquitos Lagoon

Southern California. 32°56'N, 117°15'W, San Diego County, California.

This small lagoon at the mouth of a 246-km<sup>2</sup> watershed is a public reserve that includes 142 ha of protected land.

The ocean connection was once continuous enough to support tall, vigorous cordgrass, and most of the animals were marine. Historical (1928 and 1953) aerial

photographs of the lagoon showed large bare patches (salt pans), where the rare annual goldfields (*Lasthenia glabrata coulteri*) grew, along with unique insects (tiger beetles, *Cicindella* spp., and rove beetles, *Bledius* spp.) and endangered birds nested (California least tern, *Sterna albifrons browni*).

During the early 1900s this lagoon was dissected by a bermed railroad, and a coastal highway was built along the former sand dune. These alterations modified circulation patterns, enhanced sedimentation, reduced the tidal prism, and confined the tidal inlet to the narrow space of the highway bridge. The mouth cannot migrate as sand accumulates from longshore currents, so unless bulldozed open, the mouth closes more frequently and stays closed longer, preventing tidal mixing, reducing dissolved oxygen levels and causing fish and invertebrate die-offs. The salinity of impounded water during lagoon closure shifted from hypersaline to hyposaline following

rapid development in the watershed. Housing tracts and commercial structures now cover the mesas east of the lagoon, and adjacent roads have been widened. This steady growth of impervious surface area in the watershed has increased rates and volumes of runoff, transforming wet-season flows (November to March) to year-round flows. Excess sediment has buried the upper reaches of a former tidal channel.

Cordgrass no longer occurs; instead pickleweed is the widespread dominant. Large areas with fresh sediment and reduced soil salinity are being invaded by several riparian shrubs and weeds (e.g., *Typha* spp., *Baccharis salicifolia*, *Rumex crispus*, *Xanthium strumarium*, *Polypogon monspeliensis*, *Conyza canadensis*). Although vegetation changes are more visible, the animals of the system are quicker to respond and are the best indicators of the need for restore tidal influence. The resident fish and invertebrate fauna are somewhat more resilient to fluctuations in salinity than the transient marine species (e.g., California halibut, *Paralichthys californicus*) are more subject to osmotic stress and reduced growth rates and/or mortality. Aquatic animals are at greatest risk in September and October, when water temperatures are high and oxygen concentrations quickly drop below the 4 mg/L minimum threshold for most species. Such species must recolonize the lagoon either as larvae or older individuals from nearshore refugia. Exotic and freshwater-associated fish species are becoming increasingly prevalent in historically saline lagoon habitats, further demonstrating the impacts of freshwater runoff.

**Restoring Los Peñasquitos Lagoon.** Maintaining tidal flow has been a goal since 1985 when the first plan was developed. At this time, the need to sustain tidal flushing was assumed, but not well documented. In 1987, colleagues began monitoring changes in water quality and biota associated with open vs. closed lagoon were documented. At present, fishes and invertebrates are monitored semiannually, vegetation annually, and salinity, oxygen, and temperature biweekly at permanent stations. An aquatic datalogger records oxygen and temperature, and when the mouth closes, oxygen and temperature changes are watched closely in order to determine when the bulldozer needs to be brought in to dredge the inlet.

In some years, the inlet requires repeated dredging; in other years, the mouth remains open unassisted, depending on rainfall and storm events. *The key to sustaining biodiversity is adaptive management with regular monitoring, rapid evaluation and interpretation of results,*

*rapid responsiveness of lagoon managers to researchers' recommendations, and speedy excavation of sand at the closed inlet.* Even if the bridge could be enlarged, sedimentation and excess freshwater from upstream developments would remain a serious threat.

**Update.** While some small segment of salt marsh has remained intact, brackish marsh has steadily expanded in the upper lagoon with inputs of freshwater during the dry season from the steadily urbanizing watershed. As sediment has accumulated in the main channels, the tidal prism (volume of water that moves in and out with tides) continues to diminish, making the lagoon mouth increasingly susceptible to closure. The monitoring of lagoon mouth closure, water parameters, and vegetation composition continues under the direction of the LPL Foundation and Torrey Pines State Reserve by the Southwest Wetlands Interpretive Association and the Tijuana River National Estuarine Research Reserve. Increasingly, remote cameras and real-time data delivery methods have improved monitoring and management efforts. When sand fills the ocean inlet, as it did in March-June 2013, bulldozers are brought in to re-open the mouth and restore tidal flushing, thereby preventing fish kills and related degradation. *This salt-marsh-dominated lagoon will likely need such adaptive management in perpetuity. State and citizen-based efforts make a powerful partnership.*

## Rietvlei

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Western Cape, South Africa, 33°54'S, 18°29'E.

This once-proposed Ramsar site (i.e., Wetland of International Significance) is a 428 ha, shallow ( $\leq 2$  m), formerly partly-tidal salt marsh situated north of Cape Town (a city of >3 million people). The system includes the lower reaches of the influent Diep River, the salt marsh/wetland central zone, and the Diep River lagoon and seasonal estuary. Rietvlei is Cape Town's largest and most complex urban palustrine wetland system, conjoined with the estuary of the Diep River.

The Cape Flats are sandy coastal plains of marine origin that surround Cape Town. The area was once covered by a myriad of coastal lakes and wetlands. In prehistoric times, the Rietvlei was directly connected to the sea, but this link has long been lost. Rietvlei has "evolved" from a salt marsh to a shallow, brackish coastal lake, largely due to the engineering and other developments associated with the large metropolitan

area. The tidal influence has been reduced and the freshwater influence enhanced in recent times.

The natural tidal connection has been replaced by a narrow, serpentine channel, hardened on both sides by urban development. Tidal ingress is now limited (tidal amplitude in the salt marsh is nil), with seawater only reaching the lower reaches of the salt marsh on rare occasions. Rietvlei also collects urban runoff draining from the surrounding areas. The tertiary-treated outflow from a wastewater treatment facility enters the marsh to the north-east. The natural flow from the Diep River was diverted away from the marsh by channelizing the effluent down the eastern boundary of the wetland. While routing of the wastewater effluent through the marsh would have been extremely detrimental, the hydraulic interference with the river has had a major negative impact on the marsh: When the river flows, the degraded watershed releases vast amounts of silt that are deposited in the marsh. Vegetation changes confirm that the ambient salinity of the marsh environment is declining, and former marsh zones are being “terrestrialized.”

Pumping of water in the watershed, coupled with low rainfall, have exacerbated the situation. The marsh receives vastly reduced inflows, soils dry out, and exotic plants invade, particularly the grasses *Paspalum vaginatum* and *Pennisetum clandestinum*. Rapid growth allows these plants to replace the brackish/saline flora (e.g. *Juncus kraussii*, *Sarcocornia pillansiae*, *S. natalense*, *Sporobolus virginicus*, *Triglochon bulbosa* and *Cotula coronopifolia*). During recent years, water hyacinth, *Eichhornia crassipes*, invaded large areas, and the red water fern, *Azolla*



Rietvlei aerial photo

*filiculoides*, became problematical. While release of the biological control organism, *Stenopelmus rufinasus*, has controlled *A. filiculoides*, little has been achieved using *Neochetina eichhorniae* and *N. bruchii* to control water hyacinth. Dense beds of reeds, *Phragmites australis* and *Typha capensis*, established near the wastewater treatment facility and spread rapidly across the northern reaches of the marsh. Habitat areas within the marsh are increasingly fragmented. Currently, a mosaic of environments exists, ranging from saline ephemeral pans to polluted, alien-invaded standing waters.

The degradation of Rietvlei has progressed for a long time, with frequent requests for comprehensive restoration. The lack of attention to the threats facing Rietvlei lies in governmental restructuring and funding constraints. A further factor is that rare and endangered ecosystems have not yet been afforded the priority and attention they deserve. This situation may be countered by the formation of catchment management authorities, given adequate funding and appropriate policies.

**Restoring Rietvlei.** Of the region's few remaining wetlands, all of which are degraded, Rietvlei has the greatest restoration potential. Various innovative proposals have been formulated to restore the salt marsh, including manual salting or irrigation with sea water, but none has been pursued by the local authority. The broad restoration objectives for Rietvlei include: Maintenance and restoration of the essential ecological processes and life-support systems on which the flora and fauna of Rietvlei depend; preservation of the diversity of flora and fauna occurring within the area; attraction of species which once occurred on the site; maintenance of the environmental quality of the salt marsh and its associated wetlands as habitat for wildlife, especially as feeding, roosting and breeding grounds for migrant and resident species of birds.

Central to the restoration of Rietvlei will be the choice of alternative goals: (1) restore the previous salt marsh character, or (2) conserve, without further decay, the fresh-to-brackish environment that has replaced it. Either path would require a multi-disciplinary investigation. Two other sites in the same region (a seasonal estuary and a coastal wetland) have salinity controls, following recognition of the value of saline habitat and implementation of suitable management principles. Similar recommendations for Rietvlei have been made, with a high level of confidence that objectives can be achieved.

The restoration challenges facing Rietvlei are common to those of salt marshes elsewhere in Mediterranean-type climates. Despite urban encroachment, sufficient opportunities remain for restoring saline habitat and for maintaining connectivity with the river and estuarine environments. Embodied within the recently re-written South African water laws is the requirement to *determine the "ecological reserve" needed by rivers, wetlands, estuaries and groundwater. This "reserve" is the allocation of water necessary for ecosystems to maintain their integrity in terms of water quantity, quality, habitat and biota.* While the methods for doing so are in the process of being developed, the determination of the ecological reserve for Rietvlei may go a long way towards highlighting the problems that face it.

**Update:** Rietvlei is at the mercy of a suite of anthropogenic stressors, including its close proximity to dense urban development, urban runoff, wastewater effluent, freshening of previously saline areas, sedimentation, and muted estuarine intertidal exchange. Limited funding precludes the level of research and management attention needed. The many drivers of its former robustness and resilience (resistance to change) go unrecorded. Although not on record, there have been massive fish kills, likely from a piscitoxic alga, and the mouth probably closes less often given the constant discharge of wastewater effluent. The challenges facing Rietvlei are of a generic nature. Cues from the other systems discussed here could be used to foster strategic conservation and management of Rietvlei. Sadly, affording International Significance to far-lesser wetlands near Cape Town bodes ill for the conservation of this important locality.

## Canning River

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Perth, Western Australia. -115°49'S, 31°00'W.

The Canning and Swan Rivers join within the metropolis of Perth, which is just a few km upstream of the port of Fremantle. Perth is the fastest growing city in Australia, having exceeded 2 million people in 2014.

The combined water body, the Swan River Estuary, is large and surrounded by urban development, but several tidal salt marshes occur in pockets scattered along the edges, away from the wakes of boats. The 2042-km<sup>2</sup> watershed of the Canning River produces highly pulsed river flows, both seasonally and interannually. The natural inundation regime is dominated by meteorological



Canning River aerial photo

tides, not astronomic tides, as in Southern California. Low pressure systems in winter bring about rainfall and freshwater inflow. The combination allows runoff to accumulate in the coastal marshes, creating prolonged conditions of standing, low-salinity water. In summer, the high pressure systems have the opposite effect; water flows out to sea, rainfall and streamflows are minimal, and the upper marshes dry and become hypersaline.

Alfred Cove, located along the southern shore of the Swan River Estuary, is a good reference system; here the salt marsh is dominated by *Juncus kraussii* at the inland margin and *Sarcocornia australis* at the estuary margin. Elsewhere, filling for development has eliminated such marshes, and urban runoff continues to degrade them. Pen described a pattern that he had observed throughout the estuarine wetlands, namely that *Typha orientalis* invaded and dominated wherever urban runoff was discharged to the marshes. *T. orientalis* is native to eastern Australia but not to Western Australia; hence, this displacement was considered undesirable. Zedler and Paling's experiments indicated that *T. orientalis* could not establish at the higher salinities characteristic of natural marshes, so invasion likely took place in sites with freshwater inflows. Also, *T. orientalis* seedlings were outcompeted by *Juncus kraussii* in saline soil. Hence, invasion seems limited to

areas where the soil, root zone, and canopy are disturbed. Drainage channels from urban developments have the essential qualities—runoff provides a freshwater stream along unvegetated banks. Once seedlings establish along the drainage, the more salt-tolerant adult plants can expand vegetatively, outcompeting *Juncus kraussii*. Greater salt tolerance of *T. orientalis* adults, compared to seeds and seedlings, was also shown for a southwestern United States population.

**Restoring the Canning R. salt marshes.** The annual salinity regime will be difficult to restore without cooperation among homeowners and developers upstream of these pocket marshes. *Typha orientalis* is difficult to eradicate, so prevention is the wiser strategy. Maintaining high salinities is the key. Where urban runoff is the problem, the impacts of development need to be reduced by incorporating infiltration beds for rooftop discharges and bioretention basins for street and sidewalk runoff. Bioretention areas can include swales vegetated with native species that can increase infiltration and uptake of nutrients. Such measures need to be put in place at the time of development. Future low-impact developments could become prestigious, justifying the extra cost of conservation measures.

*The ability to protect and restore salt marshes in southwestern Australia hinges on providing the normal annual and interannual salinity regimes.* Restoration sites that are bared during usually dry periods can become hypersaline and difficult to vegetate. Restoration sites that are excavated or graded during years or seasons with unusually low salinity, are susceptible to invasion by species from brackish marshes or from other regions or continents. *Juncus acutus*, a rare native plant in southern California, is a noxious pest in Western Australia, where it expands in pastures, because its needle-like leaves deter grazing. It has not yet become a problem in salt marshes. Other salt tolerant invaders are *Carpobrotus edulis*, *Pelargonium capitatum*, *Tetragonia decumbens*, *Trachyandra divaricata*, all from South Africa, and *Euphorbia pelplus* from Asia.

**Update:** Salt marshes on the Canning River are divided by the Kent Street weir, preventing upstream egress of salt water into the upper river in summer. Remnant salt marshes occur above the weir but have to cope with reduced salinities, while those below have more natural salinity ranges. A 2008 assessment found that below and near the weir, the 21.5 ha of native samphire salt marsh (*Halosarcia* and *Sarcocornia* spp.) was in good condition (considering life-form complexity, weed cover, crown death, local species natural regeneration and management pressures). However, the regional park is a vast repository of weeds. The Canning River Management Plan (1999-2007) states that past agricultural practices, clearing, urban development, fires, landfill, rubbish dumping and stormwater disposal, together with deliberate planting of exotic species in recreational areas, are the prime stressors on native fringing vegetation. The lower salinity areas were prone to weed invasion, with over 40% of the river edge having >70% weed cover.

With climate change, rainfall is declining in Perth with a 15% decline in rainfall and a 55% decline in runoff since 1975. In 2010, rainfall was so low that the weir boards remained in place all winter, reducing flushing of upstream sections and showing the first signs of salt water intrusion into the upper river. *Reduced rainfall lowered the flow of freshwater down urban drains into the river, reduced nutrient and pollutants, and increased marine influence.* Climate change could also decrease groundwater levels and increase the risk of acidification and heavy metal contamination that can result when acid sulfate soils are disturbed.

Despite reduced freshwater inflow, weeds, including *Typha* spp., persist. While local government and community groups attempt to control weeds, their work is most effective in local areas, perhaps preventing rates of spread. Canning River Regional Park Volunteers note that removing weeds allows salt marsh seed banks to self-restore, even after several years, corroborating the lessons learned in Tijuana Estuary. In 2011, a fire that burned 60 ha of the Canning River regional park resulted in regrowth of samphires over twice their pre-fire extent. Community groups followed up with weed control. The fire called attention a *hazard regarding weeds, namely, the large fuel load during the dry summer.*

With a premium on waterfront properties, further development threatens salt marshes. Small remnant salt marshes are recognized by the Australian Government's 1999 Environment Protection and Biodiversity Conservation, but even where salt marshes are protected, *adjacent developments produce runoff with urban pollutants.* While not formally documented, there is also significant concern with sedimentation. *Infill housing and new developments increase sediment loss from catchments, which enter the rivers through drains and affects elevation of salt marshes and their tidal interaction.*

The value of salt marshes both in inherent biodiversity and ecosystem services, as well as social and cultural benefits, suggests that greater commitment and intervention are required to maintain their integrity. In particular, detailed mapping of the current extent of salt marshes and assessment of changes since Pen's 1983 survey would document declines, help predict effects of climate change, and help prioritize solutions.

## Common features

Mediterranean-type salt marshes on the three continents are subjected to seasonal and interannual variability in freshwater inflows. The long dry season leads soil and water to become more hypersaline, while rainfall causes inundation, anoxia stress and hyposaline conditions. When hydrological conditions are altered, shifts in salinity lead to compositional shifts and restoration challenges.

The biota have many similarities. Closely related plants in the Chenopodiaceae (*Salicornia*, *Sarcocornia*, and *Arthrocnemum*) dominate the most saline areas, while rushes (*Juncus*, *Scirpus*, *Schoenoplectus*) and cattails (*Typha* spp.) occur in brackish areas. Dominants are evergreen

perennials and salt tolerance strongly influences their distributions. Because the vegetation is so linked to soil-salinity regimes, a slight miss in the spatial or temporal salinity pattern can produce the wrong assemblage. If the site is too saline at the time of colonization, only the most salt-tolerant species will establish. If the site is not saline enough, brackish marsh elements, including exotic species, can gain permanent footing. Brackish marsh elements tend to expand with impounded runoff and salt pans can expand without tidal flows, especially during dry years. Too little is known about the animal responses to stressors and restoration efforts.

Urbanization is a principal cause of salt marsh loss in all regions with Mediterranean-type climates, because cities developed most readily where rivers provided both a source of freshwater and navigational connections with the sea. Structures that alter water flows cause severe problems. Berms that cut through salt marshes allow sediments to accumulate and reduce tidal influence.

## Individual features

Each continent has different invasive species, and not surprisingly, they come from other continents with similar types of salt marshes. In Southern California, the exotic weeds come from Europe (*Polypogon monspeliensis*, *Parapholis incurva* and *Lythrum hyssopifolia*), South Africa (*Mesembryanthemum nodiflorum*, *Cotula coronopifolia*) and Australia (*Atriplex semibaccata*). In South Africa, the problem exotics are from central Africa (*Pennisetum clandestinum*) and South America (*Eichhornia crassipes*, *Azolla filiculoides*). In Australia, exotic plants come from South Africa and Asia.

Within and between regions, salt marshes have unique ratios of tidal:streamflow influence. Southern California marshes have a 3-m tidal amplitude (lowest low to highest high tide in a year), plus an additional 30-60 cm of anomalies due to storms. In Western Australia, the tidal amplitude is less (~0.5 m) and there is greater seasonality to the high and low water because meteorological influences exceed those of the planets. In South Africa, the Rietvlei has at most a 4-cm tidal amplitude, and the maximum tidal range at the estuary mouth is only ~0.25 m. Salinity can be too low or too high to sustain historical biodiversity.

Sedimentation differs with watershed size and condition. Tijuana Estuary, Los Peñasquitos Lagoon and the Canning River salt marshes receive too much

sediment from their erosion-prone watersheds. Where excess sedimentation is an issue, restoration should be preceded by sediment control upstream. Where sediments are in short supply, as they might become given sea level rise, overexcavation could lead to mudflat, not salt marsh habitat.

## Restoration challenges

- **Diminished habitat area.** Habitat loss is usually irreversible in urban settings; the land is no longer available for open space; it has been dredged or filled and now supports high-cost structures.
- **Habitat fragmentation.** It seems impossible to restore an ecosystem when the broader regional support system is missing and the site itself lacks connectivity with other critical landscape units, i.e., the site's own watershed, which discharges water, nutrients, and sediments, and the region's other coastal wetlands, which serve as sources of propagules for reintroduction and natural recolonization. Fragmentation of either the watershed, the regional coastal wetland network, or the individual restoration site cuts off communication and vital linkages of both biota and materials. It is not clear that rare and endangered species can withstand further urbanization and fragmentation--or recover from historical declines when restoration sites are small and isolated. Large expanses of restored wetland, deliberate reintroduction efforts of recruitment-impaired plants and—at appropriate times—the animals, and long time periods will have greater potential for recovery of regionally rare species.
- **Topography.** Some topographic changes might be irreversible, such as large structural diversions. At smaller scales, tidal creek networks can be restored to the marsh plain, to improve vegetation functions and habitat for fish-feeding. Exchanges of tidal water help maintain natural soil salinity regimes.
- **Freshwater inflows.** Probably the largest challenge is managing salinity regimes that include normal streamflows. Too much streamflow can deposit unwanted sediments and/or convert a salt marsh to a brackish system; too little sediment will not allow salt marshes to adapt to rising sea levels. But how much freshwater does a marsh need? We lack long-term experimental comparisons of sites with varied flooding frequencies and volumes. However, brief pulses, seem to be more beneficial than greatly-prolonged flows.

- **Native and exotic species.** Among the desired native species, some will colonize on their own if the site is opened to tidal flushing after seeds have been released by a nearby natural marsh. There might be a narrow window of opportunity for opening restoration sites to tidal flushing and water-borne seeds.

Regular seawater inundation protects salt marshes from most exotic species. However, upstream brackish marsh plants that are native to the region can become unwanted invaders of salt marshes during periods of lowered salinity. The high-elevation salt marsh has been most diminished by development and trampling. Revegetation is risky where soil salinities and moisture are highly variable. Infrequent tidal inundation leaves the high marsh susceptible to invasion, because heavy rainfall can leach salts and trigger seedling establishment in open spaces or under sparse canopies. Seedling establishment is often dependent on low salinity events, while expansions are usually due to vegetative growth of adult plants that are more salt tolerant than their younger life history stages.

## Conclusion

Mediterranean-type salt marshes have complicated salinity regimes that involve spatial, seasonal and interannual variability. The impacts of urbanization on three continents are similar: Excess freshwater from runoff leads to shifts in the vegetation, such that brackish marsh and exotic plant species expand at the expense of salt marsh halophytes. Once established, even the brackish species can persist, because adult plants tend to tolerate more salt. Invasion is best controlled by preventing establishment and spread.

Restoration projects that seek to restore historical topography, hydrology, substrate, and biota need a sound basis in scientific understanding of the variable salinity regime, as well as the species' various recruitment capabilities. Every remaining patch of natural Mediterranean-type salt marsh should be left intact and managed to enhance and sustain its biodiversity, as well as to improve understanding our ability to predict needs for management under unknown future conditions.

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