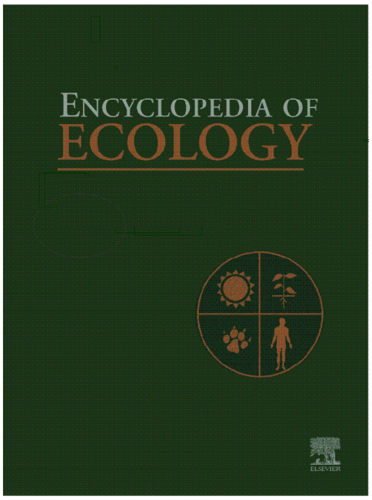

E Wolanski and R H Richmond. Estuary Restoration. In Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief), Ecological Engineering. Vol. [2] of Encyclopedia of Ecology, 5 vols. pp. [1422-1427] Oxford: Elsevier.

Wolanski E (2006) *The Environment in Asia Pacific Harbours*. Dordrecht, The Netherlands: Springer.
Wolanski E, Boorman LA, Chicharo L, *et al.* (2004) Ecohydrology as a new tool for sustainable management of estuaries and coastal waters. *Wetlands Ecology and Management* 12: 235–276.
Wolanski E and De'ath G (2005) Predicting the present and future human impact on the Great Barrier Reef. *Estuarine, Coastal and Shelf Science* 64: 504–508.
Wolanski E, Richmond R, McCook L, and Sweatman H (2003) Mud, marine snow and coral reefs. *American Scientist* 91: 44–51.
Wolanski E and Sarsenski J (1997) Larvae dispersion in mangroves and coral reefs. *American Scientist* 85: 236–243.
Zalewski M (2002) Ecohydrology – The use of ecological and hydrological processes for sustainable management of water resources. *Hydrological Sciences Bulletin* 47: 823–832.

Estuary Restoration

E Wolanski, Australian Institute of Marine Science, Townsville, QLD, Australia

R H Richmond, University of Hawaii at Manoa, Honolulu, HI, USA

Introduction

This article presents a scientific overview of the basic natural ecological processes involved in maintaining estuarine health, the technology behind efforts aimed at estuarine restoration, and examples of both success and failure.

Estuarine Ecohydrology

The health of an estuary ecosystem is determined by the dominant physical, chemical, and biological processes, sketched in Figure 1, within the estuary, as well as the natural characteristics of, and the human activities conducted within the entire river catchment upstream. The robustness of an estuary depends on the rate at which water is flushed; the longer the residence time, the greater the water quality problems. Ecological integrity also depends on the rate at which fine sediments are sequestrated in the estuary (primarily in the tidal wetlands) or flushed out to sea, as well as the efficiency with which organic matter is processed within the water column. This commonly occurs through the bacterial loop sketched in Figure 1. There are other important relationships between the estuary and its tidal wetlands. The tidal wetlands export or import different particulate and dissolved nutrients, and they are also nursery grounds for fish and invertebrates.

Human activities within the river catchment are a major driving force affecting the health of the estuary, mainly as a result of excess nutrients and sediment, a change in natural river flows from human activities, as well as land clearing and overgrazing that increase soil erosion. Such activities modify the natural flows (e.g., dams), and increase the riverine nutrient load (e.g., sewage discharge, animal waste from agribusiness such as pig farms and cattle feedlots, and fertilizers leaching from farms). All of these activities and processes also degrade the tidal wetlands because of the exchange of water and mass between the estuary and the tidal wetlands. The pressure on tidal wetlands is further increased by dredging, land reclamation for industry, and urbanization. For instance, nearly all estuarine marshes have been 'reclaimed' in the Netherlands and in Japan.

When an estuary has been degraded, its restoration cannot be successful in the long term without addressing the issues that led to its degradation. If there are several such issues, then they must all be addressed, though possibly at a different intensity, because impacts are cumulative. Restoration efforts must focus on the whole ecosystem, principally (1) managing human activities in the whole river catchment, and (2) restoring habitats to arrive at an estuarine ecosystem that is able to absorb human stresses. Managing human activities necessitates maintaining river flows, principally minimum environmental flows and controlling the timing of river floods, and limiting the riverine export to the estuary of sediment, pollutants and nutrients, so as to enable the estuarine ecosystem to function naturally. Because of the feedbacks between the estuary and its fringing wetlands, restoring estuarine habitats is essential to restoring the ecosystem health. It is also a science-based technology that is still under development.

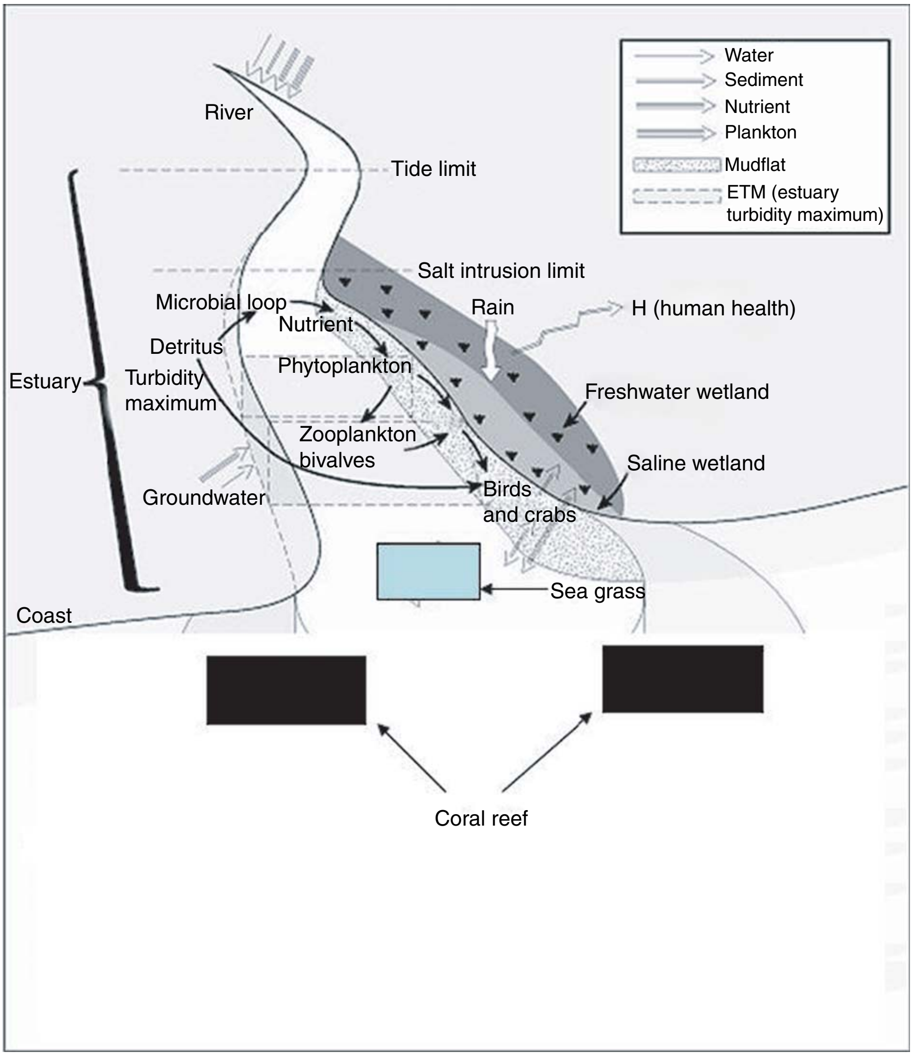

Figure 1 Habitat distribution in a typical estuary and sketch of the feedbacks between physical, chemical, and biological processes that control the health of the ecosystem. Saline wetlands can be mangroves and/or saltmarshes. Coral reefs can exist within the estuary near the river mouth and in coastal waters. Seagrass usually occur between the wetlands and the coral reefs.

In practice, this integrative management policy is not properly implemented anywhere worldwide. Nowhere in the world is there an effective mechanism enabling cooperation between water-resource managers dealing with hydrology, water supply, and hydroelectricity, city councils dealing with urbanization and waste disposal, fisheries managers dealing with commercial and recreational fisheries, and land-use managers dealing with industrial and agricultural developments within the whole river catchment. Management is still largely dictated by politics. Thus estuarine restoration is still a science-based engineering practice in its infancy. There are attempts to restore estuaries based on river catchment management as well as local estuarine habitat restoration efforts, such as for the Mersey and Thames rivers in the UK, the Rhine River in Europe, and the Chesapeake Bay in the USA, however all of these attempts have been hampered by politics. As a result, at best only a fraction of the ecological function of these estuaries has been restored. For instance macrophytes – and the biological communities of shrimp and fish that they support – cannot be restored in estuaries as long as activities in the catchment generate turbid waters.

In what follows we will describe the present techniques to restore habitats, mainly tidal wetlands, seagrass, and coral reefs.

Saltmarshes

In the USA, dredging results in the yearly accumulation of millions of tons of sediment that has to be disposed of. It has become a recent practice to place this material in shallow areas to create tidal wetlands. Basically, the dredged material is pumped onto shallow areas hydraulically. If the site is exposed to waves, it must be protected by small breakwaters often made of riprap or low-lying geotextile tubes. The dredged material is then given time to dewater and consolidate. Tidal creeks are created to allow the muddy substrate to become exposed at low tide. To create a salt marsh, the grass *Spartina alternifora* is then planted mechanically, after being harvested from natural areas or grown in a nursery. Within a few years the created saltmarsh appears similar to a natural marsh but may lack some of the biological diversity and community maturity. In the short term, the degree of success depends on whether the attributes of the dredged material are similar to those of nearby natural saltmarshes. Over longer periods, the evolution of created saltmarshes shows much unexplained variability; some marsh attributes (e.g., below ground plant biomass) continue to develop over many years, while in other marshes these attributes grow quickly during the first few years and then stabilize.

These created saltmarshes generally do not capture the biological productivity (e.g., shrimps and fish, though there are a few welcome exceptions) of natural saltmarshes. However, such created wetlands are still much preferable, and more attractive, than sea disposal of the dredged mud and the pollution it creates. There is still a need for scientific studies to improve created saltmarshes by improving plant establishment, and by linking biological communities with geomorphogical features and tidal drainage patterns. The exposure of created saltmarshes to wave erosion remains a critical factor to their relative success or failures over time; however the long-term (periods > a few years) success remains little studied. When possible, the created saltmarshes should be located behind large, shallow mud banks because they help protect the saltmarshes by dissipating wave energy.

In the southeast coast of England, UK, the preferred method of creating wetlands is by managed retreat (Figure 2). Much of the low-lying farmland is reclaimed saltmarshes, and it is protected by sea walls. These sea walls may need to be raised against a future sea level rise. This option is very expensive. Instead, the sea walls can be removed or breached, smaller sea walls relocated further inland, and saltmarshes are recreated in front of them. These dissipate wave energy and thus provide a protective buffer for the sea walls that may be built smaller. The ecological advantage is that these saltmarshes, like the natural ones, provide organic matter for fish and intertidal fauna, and they are also an important habitat for birds. There are still difficulties in establishing the plant vegetation, and this may be due to the weathering of the soils after they were reclaimed for farming over the last 400 years. Planting the vegetation with attached soil from natural saltmarshes helps to alleviate this problem. A suitable tidal drainage creek network must also be created that replicates the natural one, whereby the plants are submerged typically no more than 10 times per month.

Mangroves

The technique of creating mangrove habitat using dredged mud appears little used, contrary to the situation for saltmarshes. A welcome exception is the recent project

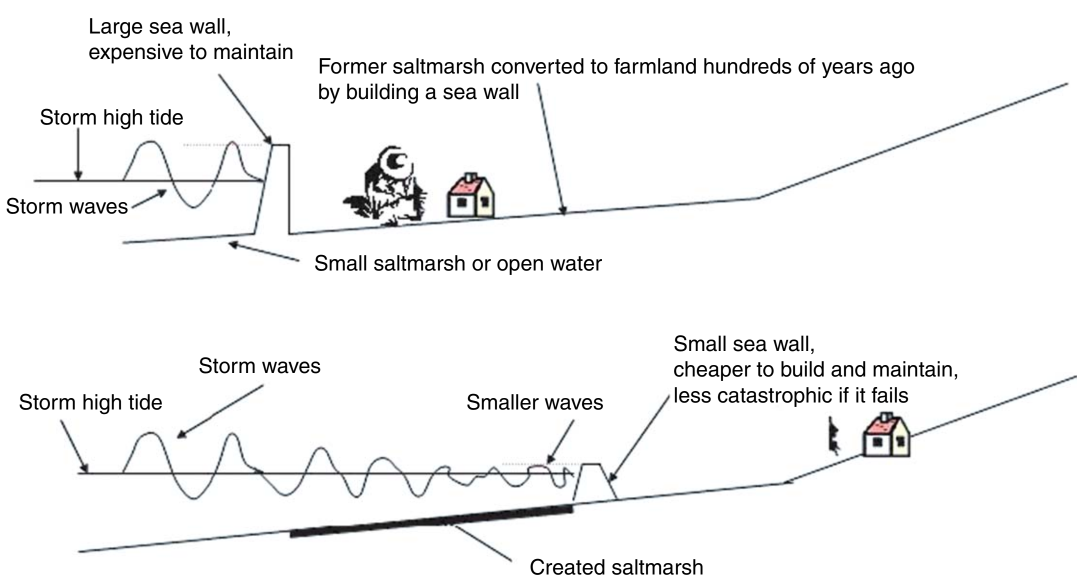

Figure 2 In England, managed retreat consists of breaching the large sea walls constructed during the last 400 years to reclaim saltmarshes for farmland, and erecting smaller sea walls landward. This creates a saltmarsh that absorbs wave energy and protects the coast, while providing ecological services such as improving the biodiversity of coastal waters.

at Port Point Lisas, Trinidad. In 1979, 500 ha of mangroves were reclaimed for port development. In 2000, a 20 ha, shallow, mud bank was bunded, filled by dredge spoil and allowed to dewater and consolidate. The bund wall was removed and the mud flat was naturally recolonized by mangrove seedlings from a nearby natural mangrove forest. Ten species of birds, including the endangered scarlet ibises, have colonized the new mud flat. There are, however, no published reports on the sustainability of the mangrove forests 3 months after removal of the bund wall; reestablishment of the forest may be slowed by the fact that no tidal drainage creek network was created.

Particularly in Vietnam and Thailand, there are thriving, long-term efforts to replant mangrove trees in former mangrove areas as well as in shallow, muddy areas along the coast. To minimize uprooting of the mangrove seedlings by waves, the seedlings are grown in a nursery and replanted on site when the trees are at least 0.5–1 m tall. The main drive is to protect the muddy coastline from coastal erosion caused by typhoons. A wave swell of period 5–8 s entering a 100-m-wide planted forest of *Kandelia candel* trees, that were planted at 1 m intervals, is reduced by 20% for 5–6-year-old trees, by 15% for 2–3-year-old trees, and 5% for 0.5-year-old trees. A 3-km-long and 1.5-km-wide (cross-shore) forest has been planted in the Thai Binh province of Vietnam; 6 years after planting the trees a 1 m wave entering the forest is reduced to 0.05 m at the coast. Without the sheltering effect of the mangroves, the waves would arrive at the coast with a wave height of 0.75 m. The process controlling wave dissipation causes wave energy to be dissipated in small eddies at the scale of the vegetation (a few centimeters) as a result of wave-induced, reversing flows around the vegetation.

The success of the planted forest in former mangrove areas depends on reestablishing a tidal drainage pattern. Usually these areas have been diked and tidal flows are restricted. Too often foresters plant the seedlings but do not reestablish a tidal flow resembling the natural pattern. Where water stagnates, the seedlings invariably stop growing and they slowly rot and die.

The seedlings are generally grown in nurseries and planted when 6 months to 1 year old. On occasions, local people have been recruited to scavenge mangrove seeds from surrounding beaches and creeks, and these are planted straightaway in degraded mangrove areas. Mixed success is achieved by this technique when planting in mangrove areas. One key factor is predation by crabs that destroy the developing bud and kill the seedling. Mortality can reach 100% at some sites, though it is more commonly 70–80%. Thus, growing the seedlings initially in a nursery is often more efficient.

Along tidal creeks near urban areas, a key problem preventing the establishment of planted mangrove seedlings is that they can be pushed over by floating debris and boat-induced waves. A solution was found and is used in Florida waterways for instance, which however is expensive, as it requires equipment and manual labor. Each mangrove seedling is protected with a thin tube wall of polyvinyl chloride. The pipe is partially split with a thin blade in order to maintain sediment levels inside the tube while the growth of the tree is not restricted, and the tube is sufficiently rigid to be driven into and anchor itself in the soft bottom sediments. The seedling grows twice as fast inside the tube than outside and is not removed by floating debris and boat-induced waves.

In logged but managed mangrove forests, such as the Konkoure River delta in Guinea, it is found that the trees will naturally reestablish themselves in the logged area provided that the bottom 1.3 m of the cut tree is left, allowing some regrowth, that several healthy trees are left in the logged area, and that the logged area is left ringed by a belt of healthy, untouched trees.

The managed mangrove forests of Matang Malaysia are commercially logged. Selected areas, planned over a 20–30 year regrowth period, are stripped-logged yearly, and seedlings of one species are replanted behind the loggers; as a result, a monoculture has resulted after 40 years of this practice and timber yield is decreasing.

No technique has yet been developed to economically and successfully replant mangroves in shrimp ponds dug in mangrove soils. Coastal shrimp pond construction is responsible for the destruction of over 50% of the mangroves in Thailand and the Philippines, yet it is unsustainable due to problems with acid soil leachate and contamination by viruses that usually result in a pond economic lifetime of 5–8 years. Further, the pond bed level is usually near low tide level, which effectively would mean that planted seedlings would immediately drown if the tide was allowed to flood the area. The soil needs to be entirely rebuilt to fill the hole and prevent acid leachate from exposed mangrove soils. Remediation is technologically feasible but economically too expensive for widespread use.

No technique has yet been developed and proven to successfully replant mangroves over oiled areas. This is because the oil has infiltrated the ground through crab holes, and it can persist there for 10–20 years.

Seagrass

Principally in the USA and Australia, there has been considerable success in restoring seagrass in clear coastal and estuarine waters. For instance, in Long Island Sound, New York, eelgrass is being replanted in a checkboard pattern consisting of squares 0.5 m by 0.5 m, alternating between unplanted and planted quadrats at 50 shoots per square. Shoots were harvested from natural, healthy donor beds and tied to jute sheets stretched between PVC pipes. These artificial beds are laid on the bottom, thereby avoiding hand planting that would stir up the sediment and reduce visibility. The jute mesh silts over and the plant establishes itself firmly. The method fails where ambient water is too turbid. To overcome this pitfall, tests are underway to co-plant eelgrass and shellfish (e.g., mussels) with the idea that shellfish feed by filtering the water and pelletizing the particulate matter. This results in improving water clarity, which in turn may improve eelgrass survival and growth. This remediation technology is still being tested and the results are not yet available to assess its suitability.

Replanting seagrass in areas with high wave energy, even if occasionally energetic, has until recently been a failure with zero survival after 2 years. A new technology has however been developed in Western Australia where a large underwater machine is driven along the bottom over healthy seagrass (*Posidonia coriacea* and *Amphibolis griffithii*) beds. The machine extracts large pods with their surrounding sediment, places them in containers, and drives them underwater to the planting areas where they are planted with the original soil around them. The results suggest a mean survival rate of 70% over 3 years. It does require of course clear waters. The technology is too new to assess if the normal ecosystem functions of seagrass are restored.

Coral Reefs

Coral reefs are complex and highly diverse ecosystems whose health is affected by both water and substratum quality. Watershed characteristics and estuarine state can greatly influence coastal coral reef community structure and function. Mangrove forests, wetlands and tidal flats can buffer the impacts of land-based activities on coral reefs, and hence their ecological role is critical in reef protection. Human activities within watersheds that increase erosion, sedimentation, runoff, nutrient input, and coastal pollution are among the greatest threats to coastal coral reefs.

Reef-building corals get most of their needed daily energy through photosynthetic products produced by single-celled, symbiotic algae living within their tissues, called zooxanthellae. As such, corals are truly solar powered, and anything that clouds the water column or coats their surfaces, such as sediments, negatively affects the colony. Additionally, many of the critical interactions on a coral reef are controlled by chemical signals between individual organisms, and between the organisms and their environment. For example, many corals only reproduce during limited periods each year, and the success of these spawning events depends on clean water. A variety of pollutants, including pesticides, oil and gasoline residues, heavy metals, sediment, and even fresh water from runoff, can interfere with egg and sperm production, fertilization, and larval development. Even if healthy larvae are produced in relatively pristine coastal areas, developing larvae drifting past an estuary can be killed or damaged by passing through areas of reduced water quality. Finally, coral larvae preparing to settle attach themselves to the reef and grow into adult colonies, are unable to recruit in areas of high sedimentation or sediment buildup. Without good water and substratum quality, both coral reproduction and larval recruitment fail, and coastal reefs go into decline.

There has been a great deal of interest in coral reef restoration within and adjacent to estuaries. Millions of dollars have been spent on such efforts, with limited positive results. The types of activities undertaken range from more passive rehabilitation efforts that focus on pollution and erosion control within adjacent water catchments, to the more interventional transplantation of corals from a healthy reef to one that has suffered damage. A number of restoration efforts have failed, with damage from collection of transplanted stock occurring at the source area, as well as death of all of the transplants when the underlying causes of coral stress and mortality were not fully addressed, or corals acclimated to one type of habitat or depth were transplanted to an area with different characteristics of light and water motion.

Restoration activities off Florida had a degree of success, where mitigation efforts consisted of stabilizing damaged corals and rubble, ‘rebuilding’ topographic relief by moving large coral heads and dislodged reef material into areas scraped clean by a grounded vessel, and transplanting both hard and soft corals to the site. In one study, a total of 11 scleractinian corals representing 8 species, as well as 30 soft coral colonies representing 12 species were transplanted. The hard coral transplants initially did well, but storm damage later caused a 50% loss of soft corals. There was recruitment of coral larvae but the coral cover remained low after 5 years. In a transplantation effort off Maui, Hawaii, 100% mortality of corals occurred over a 6 year period due to shifting sands and sedimentation. Cultivated corals and larvae are presently being produced for transplantation efforts (as well as for the aquarium trade) with the benefit of protecting natural stocks that would normally be harvested as seed material. Using cultivated material protects wild stock and also allows for the determination of whether or not the conditions have been improved enough to allow recovery to continue.

Transplantation of coral colonies or fragments, and seeding with cultivated larvae, are cosmetic solutions that may be of limited practical use over very small areas, perhaps of high economic value to diving tourism. However, genetic diversity in such instances will be low, setting the stage for future losses from environmental variability. And just as a giant redwood tree cannot be replaced by a sapling, a 200-year-old coral, killed as a result of poor land-use practices, cannot be replaced by a few fragments.

The death of corals within or adjacent to a degraded estuary is general proof that the area cannot sustain such populations, and transplanting additional colonies to replace those that were lost, without first addressing the causes of mortality, will only result in further losses. Freshwater and terrestrial sediments are carriers for a number of pollutants that are water soluble or can 'stick' to sediment particles. Following efforts at integrated watershed management, erosion control, and runoff prevention, limited transplantation efforts can be used to test if conditions have improved. The most effective efforts at coral reef restoration to date have been those that have focused on restoring those conditions that allow natural recovery to occur.

Sediment Capping

Estuarine sediment can remain polluted by heavy metals and synthetic chemicals for decades after the contaminant source has stopped. A remediation measure used particularly in Japan is to dump sand on top of the contaminated material, in order to create a 0.5–1-m-thick cap. This provides clean sediment as a habitat for organisms and it also decreases the re-entrainment of the pollutants in the water column. If the overlying water is polluted, this new sand layer can quickly become contaminated by detritus in the water column. In the long term (years), the beneficial effect of capping is reduced by erosion of the sand cap and/or mixing across the sand cap.

Conclusions

The documented losses of estuarine and coastal habitats worldwide demand our attention, and active measures to initially halt further losses and secondarily reverse the trends in favor of restoration and recovery are needed. Technology allows us to improve engineering practices on land that greatly affect wetlands and coastal communities, and also to experiment with restoration approaches to mitigate past mistakes. However, restoration is not a simple or inexpensive endeavor, and damage that can occur over weeks and months can take decades to reverse. If we are to leave a positive environmental legacy for future generations, science has to be translated into a form and format that the public and policymakers can understand and appreciate. Technology has proven to be a double-edged sword: it can damage and it can be applied to repair.

For what remains of relatively healthy estuaries and coastal waters, it is clear that prevention is the most effective approach to estuarine and coastal reef stewardship. Restoration of a particular habitat in an estuary and coastal water appears possible but generally fails if the underlying factors that cause the initial degradation or death of the habitat are not first addressed. More often that not, this requires remediation measures far upstream on land and in the river.

See also: Coastal Zone Restoration; Coral Reefs; Estuarine Ecohydrology; Mangrove Wetlands; Salt Marshes.

Further Reading

Furukawa K and Okada T (2006) Tokyo Bay: Its environmental status – Past, present, and future. In: Wolanski E (ed.) *The Environment in Asia Pacific Harbours.* Dordrecht, The Netherlands: Springer.
Hazelden J and Boorman LA (2001) Soils and 'managed retreat' in south east England. *Soil Use and Management* 17: 150–154.
Paling EI, van Keulen M, Wheeler KD, *et al.* (2001) Improving mechanical seagrass transplantation. *Ecological Engineering* 18: 107–113.
Richmond RH (2005) Recovering populations and restoring ecosystems: Restoration of coral reefs and related marine communities. In: Norse E and Crowder L (eds.) *Marine Conservation Biology: The Science of Maintaining the Sea's Biodiversity.* Washington, DC: Island Press.
Saenger P (2002) *Mangrove Ecology, Silviculture and Conservation*, 376pp. Dordrech, The Netherlands: Kluwer Academic Publishers.
Streever WJ (2000) *Spartina alterniflora* marshes on dredged material: A critical review of the ongoing debate over success. *Wetlands Ecology and Management* 8: 295–316.
Wolanski E, Boorman LA, Chicharo L, *et al.* (2004) Ecohydrology as a new tool for sustainable management of estuaries and coastal waters. *Wetlands Ecology and Management* 1: 235–276.
Wolanski E and De'ath G (2005) Predicting the present and future human impact on the Great Barrier Reef. *Estuarine, Coastal and Shelf Science* 64: 504–508.
Wolanski E, Mazda Y, Furukawa K, *et al.* (2001) Water circulation through mangroves and its implications for biodiversity. In: Wolanski E (ed.) *Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef.* Boca Raton, FL: CRC Press.