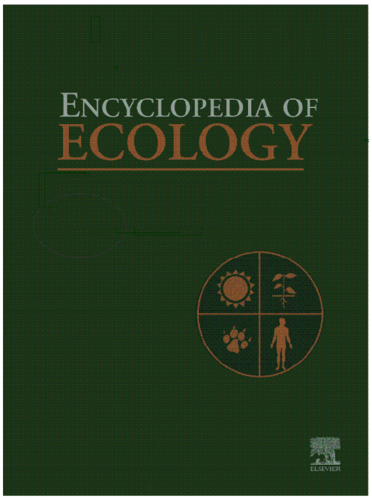

E Wolanski, L Chicharo, and M A Chicharo. Estuarine Ecohydrology. In Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief), Ecological Engineering. Vol. [2] of Encyclopedia of Ecology, 5 vols. pp. [1413-1422] Oxford: Elsevier.

suspended sediment load, eutrophication, species invasion, and disease. The bay's responses to these forces were slow at first, but with the steady increase in the human population in the bay watershed and with its adherent development, the signs of a state change were dramatically evident. The oyster reefs, a major benthic subsystem or habitat that had dominated the bay for centuries, began to decline rapidly or crash. The benthic-dominated food web was replaced by a planktonic food web. Management efforts to restore the initial oyster-dominated system did not work, probably because they had a single species focus and because ecosystems are strongly nonlinear which means the path to restoration is different from that leading to the initial change of state and many more components of the ecosystem are involved in addition to the oysters.

See also: Mangrove Wetlands; Salt Marshes.

Further Reading

Alongi DL (1998) *Coastal Ecosystem Processes*. Boca Raton, FL: CRC Press.

Attrill MJ and Rundlle SD (2002) Ecotone or ecocline: Ecological boundaries in estuaries. *Estuarine, Coastal and Shelf Science* 55: 929–936.

Dame RF, Childers D, and Koepfler E (1992) A geohydrologic continuum theory for the spatial and temporal evolution of marsh-estuarine ecosystems. *Netherlands Journal of Sea Research* 30: 63–72.

Dame RF, Chrzanowski T, Bildstein K, *et al.* (1986) The outwelling hypothesis and North Inlet, South Carolina. *Marine Ecology Progress Series* 33: 217–229.

Dame RF and Prins TC (1998) Bivalve carrying capacity in coastal ecosystems. *Aquatic Ecology* 31: 409–421.

Day J, Hall C, Kemp W, and Yanez-Arabcibia A (1989) *Estuarine Ecology*. New York: Wiley.

Gunderson LH and Pritchard L (2002) *Resilience and the Behavior of Large-Scale Systems*. Washington, DC: Island Press.

Lotze HK, Lenihan H, Bourque B, *et al.* (2006) Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science* 312: 1806–1809.

Mann KH (2000) *Ecology of Coastal Waters*, 2nd edn. Oxford: Blackwell Science.

Estuarine Ecohydrology

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The Failure of Present Estuarine Management from Ignoring Ecohydrology
An Estuarine Ecohydrology Model
Estuarine Ecohydrology Applications
Coral Reef Ecohydrology Model
Coral Reef Ecohydrology Applications
Conclusions
Further Reading

The Failure of Present Estuarine Management from Ignoring Ecohydrology

Throughout the world, estuaries and coastal waters have experienced environmental degradation. Present proposed remedial measures based on engineering and technological fix have been unable to restore the ecological processes of a healthy, robust estuary and, as such, will not reinstate the full beneficial functions of the estuary ecosystem. The successful management of estuaries and coastal waters requires ecological engineering, that is, an ecohydrology-based, basin-wide, approach. Ecohydrology is the science that relates hydrological processes to the biological dynamics of ecosystems at various spatial and temporal scales. The ecohydrology concept was developed in the framework of UNESCO's International Hydrological Programme (IHP). It hypothesized and empirically confirmed in a number of demonstration sites that the ecological services of rivers and lakes can be restored by using hydrology to regulate biota dynamics and vice versa. The synergic integration at the basin scale of various ecohydrological measures based on ecological needs provides the scientific background for twinning ecosystem variables in order to enhance the carrying capacity and the resilience of ecosystems while promoting positive socioeconomic feedbacks.

Implementing the ecohydrology approach necessitates getting away from present management practices based on regulation focused on the geography (e.g., individual municipalities or counties) or on individual, specific activities (e.g., farming and fisheries, water resources, urbanization, shipping) without integrating among localities and users so as to consider the ecosystem. Without this change in thinking and management concept, estuaries and coastal waters will continue to degrade, whatever integrated coastal management plans are implemented because these ignore the basic ecology fact that the land, the river, the estuary, and the coastal waters are connected by being in the same ecosystem.

Can science-based management save estuaries and coastal waters? About environmental management the main thing that can be reliably managed is the human behavior and practices. The main thing that ecological engineers can do is to highlight the role of ecohydrology in offering a robust, science-based way to quantify both the present human impact on the degradation of estuarine and coastal ecosystems and the likelihood of success of various remediation measures in improving the health of these ecosystems. Remediation measures include changing human behavior and practices in using the land and water resources. These measures also include boosting the ecosystem robustness by manipulating the ecosystems so as to reinforce the beneficial ecological feedbacks in these ecosystems. The eventual success of these measures relies on adopting an ecohydrological approach.

Estuaries and coastal areas are traditionally among the most highly impacted waters. For centuries human populations have settled and have benefited from the services provided from these highly productive ecosystems. During the last century, the human population worldwide has increased by a factor of about 10 in coastal areas of many developing countries and probably a factor of 4 for most developed countries, as a result of natural population growth and migration. As a result the carrying capacity of coastal ecosystems is exceeded and this has commonly led to a serious environmental degradation of estuaries and coastal waters worldwide. This is best demonstrated for the megacities and harbors in the Asia Pacific region where the best of engineering practices have failed to provide a healthy environment to 100 million people. In most sub-Saharan African countries, migration to the coast is still increasing the coastal population yearly at typically 5–8% because coastal areas provide free access to food (fisheries) and timber (mangrove trees) and hope for jobs in harbors and coastal cities.

In view of this ever-increasing human impact on coastal ecosystems, corrective or preventive measures based on an ecohydrological approach should be considered instead of just engineering measures as has been the general approach so far. This does require changing the legislation that is a quagmire for the management of estuarine and coastal waters. The successful implementation of an ecohydrology approach to managing estuaries and coastal waters must be based on a sound scientific knowledge of the ecosystems functions and dynamics.

The ecohydrological approach has been tested successfully in various locations and systems (salt marsh estuary, mangrove estuary, and coral reefs) around the world, particularly in the Guadiana Estuary in temperate Portugal and Darwin Harbor and the Great Barrier Reef in tropical Australia. The health of these ecosystems was demonstrated to depend on the connectivity between estuarine and coastal waters, on the links between physical and biological processes, on the drainage basin hydrology, and on the disturbance caused by human activities. It was possible at these sites to quantify the human impact on the ecosystem health, and the impact of remedial activities.

Major observed impacts in estuarine and coastal ecosystems are the increasing eutrophication risk, toxic algal bloom events, muddiness and siltation of estuaries and coastal erosion, and also modifications in biodiversity resulting in the loss of traditional ecosystem services (e.g., coastal fisheries) and having negative socioeconomic impacts (e.g., the loss of income and employment for coastal communities). The degradation is most dramatic for coastal coral reefs located within the estuary and in its coastal waters (**Figure 1**). Coral reefs possess the highest diversity of any marine and most terrestrial ecosystems and they greatly benefit humanity by building islands and atolls, by protecting shorelines from coastal erosion, and supporting fisheries and diving-related tourism. Coastal reefs are being destroyed at an accelerating and unsustainable rate worldwide (e.g., up to 50% in the last 15 years in some Asian countries) by human activities that can be devastating (e.g., mining for limestone, fishing with explosives and cyanide, infilling for urbanization) or threatening but possibly manageable (e.g., increased runoff of mud, nutrients, and pesticides from adjacent river catchments, overfishing, and global warming). The present coral reef strategy principle relies on drawing a line around coral reefs and protecting the corals inside that line. It is politically convenient and it ignores the fact that the land and the reef are ecologically connected through the rivers. It thus invariably fails worldwide wherever the reefs are impacted by runoff that is modified in quantity and quality by human activities on land.

Intensive agriculture practices, urban sewage, and manure from pig farms and cattle feedlots provide quantities of nutrients that reach the estuary by runoff or as groundwater and can cause eutrophication to a level dependent on the robustness of the estuary. The riparian vegetation upstream and the vegetation in salt marshes and/or mangrove swamps downstream play a bottom-up role as buffers that retain nutrients and reduce the load remaining in the estuary. Also, filter-feeders and grazers (e.g., fish and bivalves) can exert a top-down control on primary producers' biomass (**Figure 2**) and improve water quality. Indeed, bivalve suspension feeders have also been suggested as a means to control algal blooms, in both the marine and freshwater regions of the estuary. However, bivalve excretion increases the pool of nutrients available for other primary producers as the macroalgae like *Ulva* sp. or the colony-forming *Phaeocystis* sp.

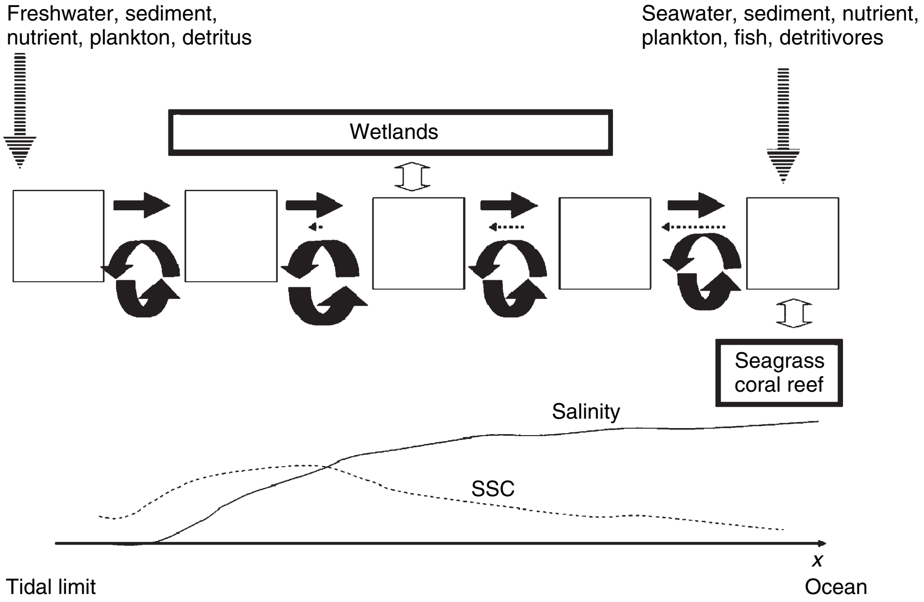

Figure 1 The physical submodel schematizes the estuary as a series of cells connected to each other by advection driven by both the river discharge (straight thick arrows) and the salinity-induced currents (broken thin arrows) and by tidal mixing (curved arrows). The open boundary conditions are located at the tidal limit where a riverine flux of water and waterborne particles is imposed, and at the mouth where an oceanic flux is also imposed. The estuary also exchanges water and waterborne particles with the wetlands (perimarine wetlands, mangroves, and salt marshes) and the seagrass and the coral reefs. The suspended solid concentration (SSC) commonly has its largest value in the turbidity maximum zone. The salinity increases in the estuary toward the mouth.

Studies also provide evidence that changes in the river discharge impact on the structure of estuarine plankton, fish, and bivalves communities. In fact, the response to low-flow periods has been recognized as one of the most important factors in structuring biota, both in the estuary and coastal waters. During low-flow periods, a decrease in the concentrations of those nutrients reaching the sea may occur, especially in dammed rivers, since the silicates (Si) trapped in the dam is not reintroduced downstream in the system, as may occur with N and P (as consequence of the use of fertilizers in agriculture). In such situation, Si can be limiting to the growth of diatoms, and may contribute to the occurrence of toxic algal blooms. The reduction of low flows by dams and irrigation is thus a threat to the health of estuarine ecosystem.

Dams reduce river flows. These high river discharges are ecologically important because they 'feed' the coastal waters with sediments and nutrients, ensuring the adequate nutrients Si:N:P ratios and promoting coastal waters productivity There is increasing evidence that coastal fisheries landings are related to the high river flows discharge and not climate factors, as has been demonstrated for South Portugal, the East Mediterranean coast, the Black Sea, and the Gulf of Carpentaria. For instance in the Guadiana Estuary and coastal waters following high-discharge periods, catches are dominated by planktivorous fish like the anchovy (*Engraulis encrasicolus*) and the sardine (*Sardina pilchardus*). This is because high river discharges promote primary and bacterial production from increased nutrient loading and organic matter loading. They also increase larval and juvenile survival because higher turbidity associated with greater sediment loads reduces predation. They facilitate the retention of early life-history stages and increase the survival. They provide an environmental clue (salinity gradients) for shrimps and fish to migrate towards the estuary where tidal wetlands (salt marshes and mangroves) are used as a nursery for the larvae and juveniles. In areas where the continental shelf is narrow, the effects of freshwater runoff can reach the upper continental slope, especially during upwelling events, increasing larval physiological condition and consequently decreasing larval mortality. These larvae can find abundant food in winter because during this rainy period the freshwater discharge is usually high, promoting salinity stratification and the development of a shallow surface mixed layer where phytoplankton that can bloom long before the spring phytoplankton blooms occur.

These examples show that the regulation of estuarine and coastal biota processes is highly dependent on the river discharge. This offers politicians and water resources managers the option to try to improve estuarine ecosystem health on a case to case basis by modifying mostly one variable.

The estuarine ecosystem modeler is faced with complex processes and feedback processes between the physics and the biology, which in practice cannot be

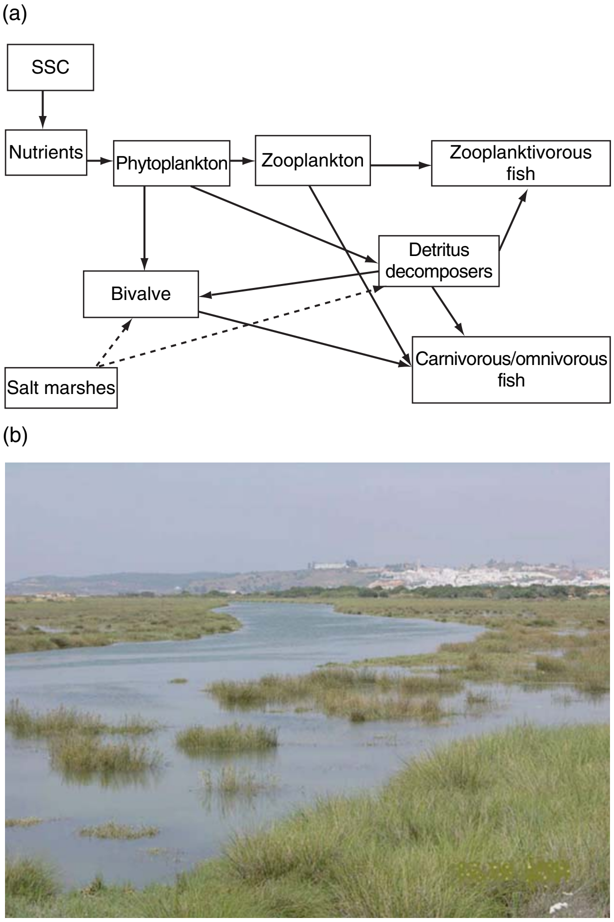

Figure 2 (a) The biological submodel for the Guadiana Estuary, Portugal. The salt marsh is modeled as a source of detritus and juvenile bivalves (broken arrows). At death all organisms become detritus (not shown). SSC, suspended solid concentration. (b) Photograph of Guadiana Estuary salt marshes and encroaching urbanization in the background.

fully quantified because the data are inadequate. For this reason, models should only be used as tools that help to explain the reality, steer field researchers towards studying key processes that most control estuarine health, and help quantify the impact of human activities on the health of estuarine ecosystems. Models should not be seen as able to replace reality and the need for field observations. Governments often want to cut budgets for field research and instead promote the cheaper option of modeling. Estuarine ecosystem models are simply unable to provide reliable answers without field studies.

Estuarine ecohydrology models are based on the knowledge and quantification of physical and biological processes controlling the ecosystem. They can quantify the likely effectiveness of ecohydrology solutions for eutrophication by two opposite ecological approaches, namely top-down control on vegetation by herbivores, or bottom-up control of nutrients loads. They can also quantify the likely effectiveness of dealing with eutrophication by regulating the river flow, for example, allowing freshets. The control of nutrient input into the system can be obtained by creating or restoring wetlands, which will act as buffers and trap nutrients. These wetlands, when located near the coast, also protect the coast from erosion, thus protecting inland infrastructures and coastal populations. The cumulative effect of wetland creation and controlling the riverine nutrient loads through changes in land-use practices invariably lead to an efficient decrease in nutrients in the estuary, often larger than the sum of the two impacts individually. For each of these solutions and for each case, models should be used before field implementation of the remediation activities to assess likely improvements in the health of the ecosystems and to compare these with observations, so as to be able to separate human from climate effects.

A top-down approach can be considered and modeled for control of eutrophication, that requires the knowledge about the ecological food web in the area: who eats who, when, and how much. The quantification of these processes and relations is basic to the selection of the most effective grazer species. In some cases manipulation of the food web could be necessary, for example, (1) controlling the density of the predator species; (2) allowing the herbivore species – that will control the vegetation growth – to become more abundant, and (3) introducing bivalves to filter the water and reduce the risk of toxic algae blooms. Such is the case in San Francisco Bay where eutrophication is inhibited because half of the water is filtered daily by bivalves that were accidentally introduced.

Toxic algal blooms are frequent in nutrient-enriched estuaries and, in particular, in dammed estuaries, and estuaries with reduced flushing and very long residence times. For instance, Tokyo Bay in Japan and the Pearl River estuary in China have respectively about 100 and 200 days of toxic algae blooms every year in various areas. Bivalves have been successfully tested to control phytoplankton blooms and reduce eutrophication and toxic algal blooms. Another way to control algal blooms is to generate freshets (i.e., freshwater discharge pulses). During freshets, with the duration of typically few days, the amount of nutrients available for phytoplankton growth increases, causing a decrease in competitive exclusion mechanisms and the consequent increase in phytoplankton diversity. In turn this promotes the growth and the diversity of zooplanktonic species. Consequently, more zooplankton species may play a regulatory role by controlling phytoplankton density and ‘avoiding’ the phytoplankton growth of just few species, therefore reducing the risk of toxic algal blooms.

The use of freshets to control algal blooms requires a profound knowledge of the system on a case to case basis, in order to determine the timing, the magnitude, and the duration of the freshet. A poor timing of freshets could negatively impact species that use the estuaries and its tidal wetlands as a nursery ground, if the freshet interferes with the natural recruitment of these species, for instance by flushing out the eggs and larvae.

Estuarine ecohydrology models have been developed and verified for few ecosystems, recently for the Guadiana Estuary in Portugal and Darwin Harbor and the Great Barrier Reef in Australia in a program supported by UNESCO-ROSTE, NOAA, AIMS, and the University of Algarve/CCMAR. The explicit aim was to offer science-based solutions to management. The ecohydrology models due to its holistic approach is a tool that aims to facilitate an interaction between scientists, economists, the public, and decision-makers to promote the ecologically sustainable development of an estuary and its coastal waters.

An Estuarine Ecohydrology Model

This model is based on the dominant ecohydrological processes in tidal estuaries. The model is best suited to estuaries that are fairly well mixed vertically. In practice this constraint is adequate for many applications because critical conditions in estuaries commonly arise during low-flow conditions brought upon by dams and water extraction. These conditions are exacerbated by excess nutrients from, typically, sewage discharge, effluent from feedlots, and fertilizers from farming. Thus the physical submodel, sketched in **Figure 1**, views the estuary as a series of connecting cells that exchange water by advection as result of the river runoff and the saltwater inflow, and by tidal mixing. The upstream cell receives freshwater, sediment, nutrient, and freshwater plankton. The downstream cell receives seawater and marine sediment, nutrients, and plankton. Cells can also exchange water and particulates with fringing wetlands both in the fresh and the saline region of the estuary. The physical processes and the open boundary conditions control the salinity distribution and the suspended solid concentration (SSC; both are sketched in **Figure 1**). An estuarine turbidity maximum (ETM) commonly prevails. The salinity and SSC distribution vary both spatially and temporally.

This physical submodel model is linked to an ecological submodel that is adapted to local conditions and is based on the results of field studies. This submodel is also a simplification of the processes in estuaries, focusing on the dominant processes in terms of mass transfer. The resulting ecological submodel for the Guadiana Estuary is shown in **Figure 2** and that for Darwin Harbor in **Figure 3**. **Figures 2 and 3** show the minimum level of complexity of the model that is necessary to capture the ecology of these estuaries. There are important features that are found in both temperate and tropical estuaries, namely (1) the importance in turbid waters with a very long residence time of the suspended solid in releasing for biological productivity particulate nutrients, (2) the dominance of the microbial loop especially near the ETM zone, (3) the role of detritivores and bivalves, and (4) the role of wetlands as a source of detritus as well as mainly a nursery ground. These tidal wetlands are made up of mangroves in the tropics and salt marshes in the temperate climates. A key commonality also is the importance of river floods, even short-lived ones, in attracting coastal fish to migrate up-estuary by kinesis or taxis by swimming following environmental clues, primarily salinity gradients.

The model has been successfully verified against field data for these two estuaries.

Estuarine Ecohydrology Applications

For the Guadiana Estuary the model is particularly useful in quantifying the importance of short freshets in enhancing plankton and fish diversity (**Figure 4**). It is also useful in quantifying the importance of tidal wetlands (salt marshes) in reducing eutrophication (**Figure 5**). This demonstrates clearly two management strategies that can be used to alleviate eutrophication and promote biodiversity and estuary robustness, that is, create freshets from the dam and creating or restoring tidal wetlands. The ecology submodel also highlights the key role of bivalves in filtering the water, suggesting another strategy of manipulating bivalves to reduce eutrophication.

Similarly for Darwin Harbor the model is useful to assess to what degree the estuarine ecosystem health may degrade – and what level of human disturbances in the drainage area is admissible to maintain a reasonable ecosystem health – as a result of future human activities in the catchment, particularly the urbanization of Darwin, the impact on the estuarine health of nutrient enrichment from sewage discharges, and the destruction of tidal wetlands (mangroves) for shipping and industry.

Coral Reef Ecohydrology Model

The sustainable development of coastal waters and coral reefs is dependent on development policies for land and water resources. To quantify this dependency, it is necessary to understand the key biological and oceanographic processes governing the health of these coastal ecosystems. These processes are then incorporated in a coral reef ecohydrological model that can predict reef health. The immediate use and role of this model is to help answer two key questions for managers. These two key questions are as follows: (1) to what extent do changes

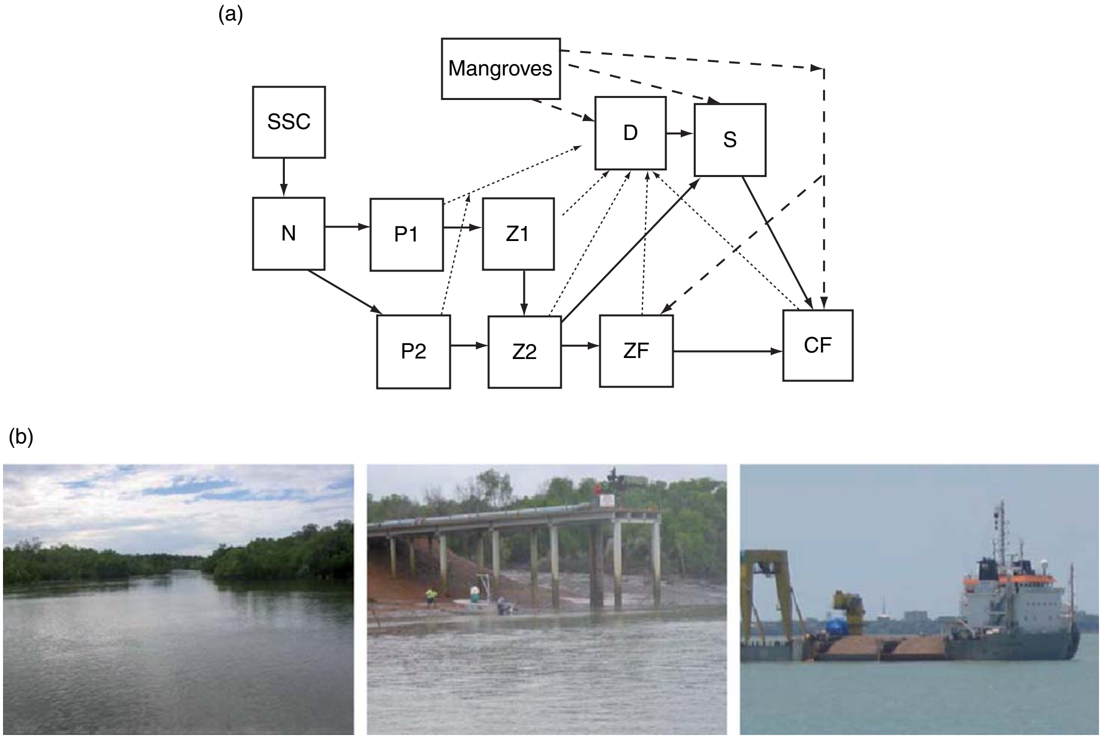

Figure 3 (a) The ecology submodel for tropical Darwin Harbour, Australia. SSC, suspended solid concentration; N, nutrients; P, phytoplankton (two dominant species with different turnover rates); Z, zooplankton (two dominant species with different preys and turnover rates); D, detritus; S, detritivores; ZF, zooplanktivorous fish; CF, carnivorous fish. The mangrove swamp is modeled as a source of detritus as well as a source of young detritivores and fish (thick broken arrows). At death all organisms become detritus (thin broken arrows). (b) Photographs in Darwin Harbour of pristine mangroves in traditional Aboriginal land on the west bank (left), aquaculture industries encroaching in mangroves in the southern region (middle), urbanization and port development on the east bank removing all natural habitats (right).

in quality and quantity of terrestrial runoff lead to reef degradation by generating phase shifts – the process by which areas formerly dominated by corals are overgrown by algae; and (2) is the reef capable of sustaining or rebuilding its biodiversity by self-seeding if remediation measures are implemented on land and in rivers to moderate the human impact?

The estuarine ecohydrology model has been modified and applied to coastal coral reefs that are subject to human impacts from (1) land runoff resulting in an increase in suspended sediment, increased water turbidity, and increased nutrient concentration, and (2) from global warming resulting in increased bleaching events in summer. The coral reef physical submodel (Figure 6) is more complex than that of estuaries because it considers also river floods and tropical cyclones that both negatively affect coral reefs, and the oceanographic connectivity between reefs that enable self-seeding as well as the connectivity, that is, the exchange of coral planulae between reefs. The biological submodel (Figure 7) is based on the competition for hard substrate space between the algae and the coral. The coral is preyed upon by crown-of-thorns starfish, whose population dynamics is also modeled. Algae are preyed upon by herbivorous fish that in turn is preyed upon by carnivorous fish that is harvested by people. Suspended sediment concentration (turbidity) and nutrients modulate all these processes. Additionally the success of recruitment of juvenile coral decreases with increasing algal cover on the hard substrate. Global warming results in an increased mortality of adult corals.

Coral Reef Ecohydrology Applications

This model was developed for the Great Barrier Reef and successfully verified against an extensive data set. It has also been applied to reefs in Micronesia (Guam, Palau, and Pohnpei).

The people of Micronesia have centuries, as opposed to decades in the Great Barrier Reef, of experience in dealing with coral reefs upon which their livelihood depends. They have traditional management policies that highlight the need to manage human activities that affect coral reef

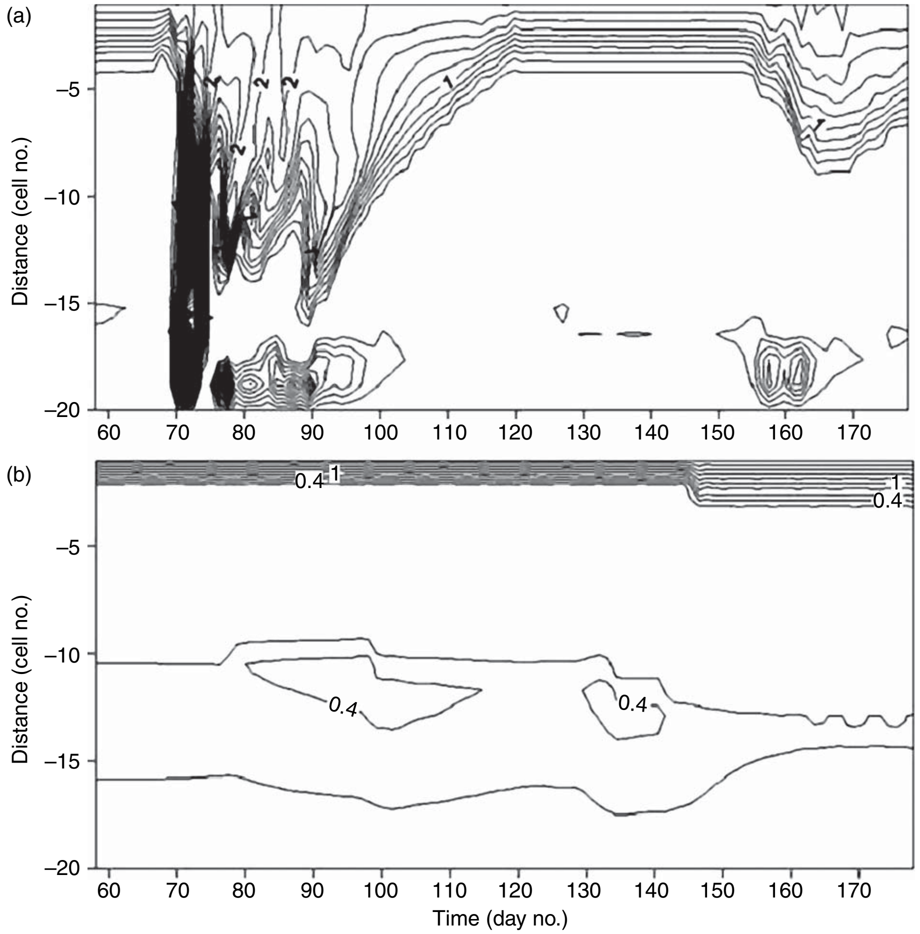

Figure 4 Predictions of the along-channel distribution (cell 20, river mouth; cell 1, tidal limit = 60 km) of zooplanktivorous fish biomass in the Guadiana Estuary, Portugal, in 2004, (a) without and (b) with the Alqueva dam. The dam construction was completed in 2003 and in 2004 the dam suppressed all freshets. The 'without dam' calculation assumes natural river hydrographs that were calculated from rainfall data. The 'with dam' calculation uses the observed river runoff as the open boundary condition at the tidal limit. To convert biomass to concentration for fish $2.8 \approx 2.87\,\mathrm{g\,cm^{-2}}$.

ecosystems. In many islands, the people have direct ownership of coral reefs and the fisheries they support. For Micronesia, the model highlighted the beneficial role of mangroves, and this has resulted in a legislative protection of mangroves in at least one state (Palau). For Guam, Palau, and Pohnpei, the study demonstrated the need for integrating land-use and coral reef management. In islands where some form of traditional leadership still exists, this model has measurably helped in improving local environmental planning because these traditional leaders take into account the long-term, multigenerational impacts of activities in the development of environmental policies. Thus ecohydrology and ecological engineering are accepted and becoming a powerful tool in such islands.

For the Great Barrier Reef of Australia, the model suggests that land use has contributed to the degradation of the health of the Great Barrier Reef and to an increased frequency and intensity of crown-of-thorns starfish infestations. The model also predicts that the health of the Great Barrier Reef will significantly worsen by the year 2050 as a result of global warming. The model demonstrates to managers and politicians that it is worth improving land-use practices to recover the health of the Great Barrier Reef ecosystem. Indeed the model suggests that much-improved land-use practices will enable some regions of the Great Barrier Reef to recover, even with global warming. However, in the longer-term the situation is more gloomy, because the model suggests that if global warming proceeds unchecked only biological adaptation can prevent a collapse of the Great Barrier Reef health by the year 2100.

This ecohydrology model can be used to quantify the effectiveness of remedial measures on land. In theory thus ecological engineers can offer to economists and politicians the hard science data on ecosystem health that are needed to

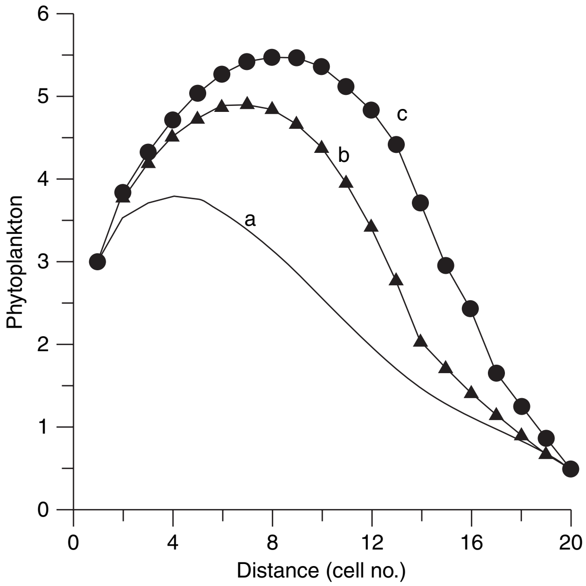

Figure 5 Predictions of the along-channel distribution (cell 20 = river mouth; cell 1 = tidal limit = 60 km) of phytoplankton biomass for (a) low-flow conditions ($2\,m^3\,s^{-1}$) in summer in the Guadiana Estuary, Portugal, for (b) a hypothetical doubling of the riverine nutrient inflow as a result of planned irrigation farming using Alqueva dam water, and (c) with in addition the removal of the salt marshes. To convert biomass to chlorophyll *a* concentration $3.5 \approx 7.8\,\mu g\ l^{-1}$.

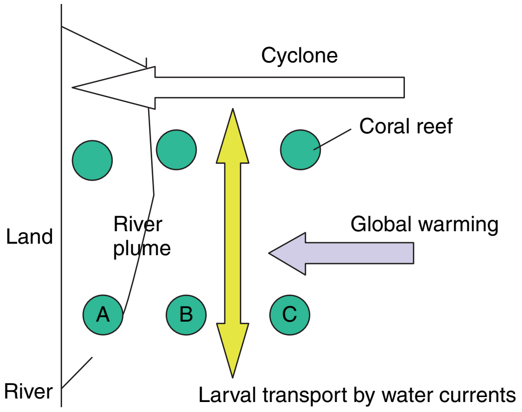

Figure 6 Sketch of the dominant physical processes in the coral reef ecohydrology model. A, B, and C represent coral reefs with increasing distance from the coast.

develop management policies that integrate socioeconomics and ecosystem health, as a first step towards planning an ecologically sustainable development. In practice however for the Great Barrier Reef and most corals reefs worldwide outside of a few islands in Micronesia, ecological engineering may have little impact because of two phenomena. Firstly there is the 'tragedy of the commons' where few take any responsibility but everyone has ownership – this is the same problem which has resulted in the collapse of fisheries worldwide. Secondly there is uncertainty in the science of cause and effects of reef degradation – some of that uncertainty is inherent to science, much is purposely manufactured – and this uncertainty helps politicians and decision-makers to justify ignoring the problem and implement no remedial measures.

Conclusions

Estuarine and coastal habitats are increasingly degraded worldwide. Ecohydrology demonstrates unambiguously that the land, the river, the estuary, and coastal waters are components of the same ecosystem. They are connected through a number of physical and biological processes that determine environmental health. Traditionally, the estuarine management strategy relies on technology and engineering fixes and it neglects ecohydrology principles; these strategies invariably fail to maintain ecosystem health and the ecological services that these ecosystems provide. Coastal coral reef management strategies worldwide also neglect ecohydrology science and also invariably fail. Ecohydrology science offers a number of solutions, including top-down and bottom-up ecological manipulation as well as the use of created or restored wetlands to help restore the health of estuarine and coastal waters. Combined with some technological fixes, such as the creation of freshets and smarter land-use, ecohydrology science offers an ecologically sustainable management strategy for estuaries and coral refs. Worldwide the implementation of this science-based strategy will most likely stall, and estuaries and coastal waters will continue to degrade, until a political solution is found to the quagmire (i.e., the present estuarine and coastal management framework) which basically ignores ecosystem ecology.

Estuarine and coastal areas suffer an increasing pressure from anthropogenic activities. Modifications of physical and chemical parameters affect biodiversity and hamper the traditional uses and services by local populations. Estuarine and coastal management relied, traditionally, on technology and engineering fixes, neglecting the ecological equilibrium of the systems. Alternatively, ecohydrology science, based on the interplay between hydrology and ecology, offers a number of sustainable and long-lasting solutions to increase the robustness and to restore the health of estuarine and coastal waters. Estuarine ecohydrology models aiming to facilitate the interaction between scientists, economists, the public, and decision-makers have been developed and verified for a few ecosystems, recently for the Guadiana

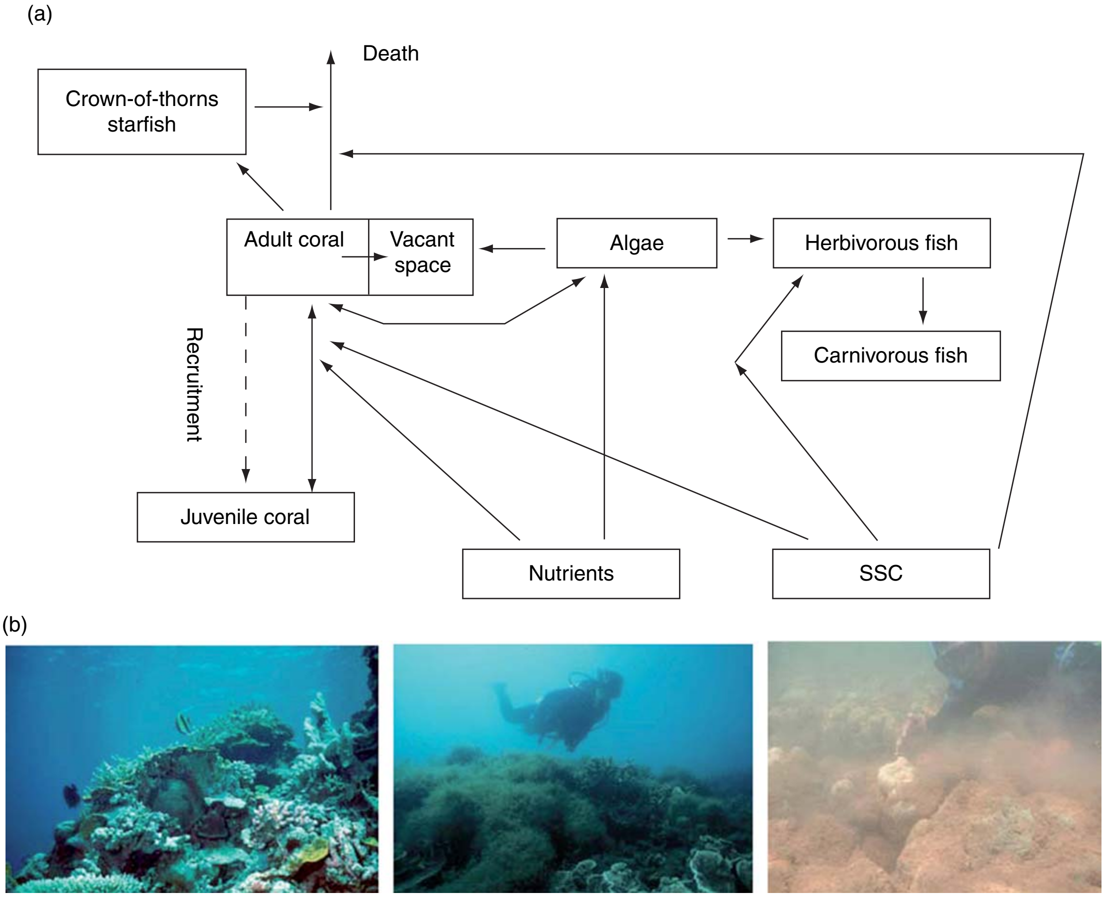

Figure 7 (a) Sketch of the dominant biological processes in the coral reef ecohydrology model where SSC indicates the suspended sediment concentration that is a measure of turbidity. (b) Underwater photographs of a healthy coral reef (left), a coral reef overgrown by algae – this is a stable ecological state as long as poor water quality prevails (middle), a coral reef smothered and killed by mud from eroded soil from the adjoining river catchment (right).

Estuary in Portugal and Darwin Harbor and the Great Barrier Reef in Australia, under a scientific program supported by UNESCO-ROSTE, NOAA, AIMS, and the University of Algarve/CCMAR.

See also: Coastal and Estuarine Environments; Estuary Restoration; Fishes as Indicators of Estuarine Health and Estuarine Importance.

Further Reading

Chícharo L (2004) Estuarine and coastal areas: How to prevent degradation and restore. In: Zalewski M and Wagner-Lotkowska I (eds.) *Integrated Watershed Management – Ecohydrology and Phytotechnology*, ch. 13, pp. 202–208. Japan, IHP: UNEP, UNESCO.

Chícharo MA and Chícharo L (2004) Estuarine and coastal areas: How and what to measure. In: Zalewski M and Wagner-Lotkowska I (eds.) *Integrated Watershed Management – Ecohydrology and Phytotechnology*, ch. 8, pp. 124–131. Japan, IHP: UNEP, UNESCO.

Dyer KR (1997) *Estuaries. A Physical Introduction*. Chichester, UK: Wiley.

Erzini K (2005) Trends in NE Atlantic landings (southern Portugal): Identifying the relative importance of fisheries and environmental variables. *Fisheries Oceanography* 14(3): 195–209.

Hutchinson GE (1961) The paradox of the plankton. *The American Naturalist* 95: 137–147.

Kimmerer WJ (2002) Physical, biological and management responses to variable freshwater flow into the San Francisco estuary. *Estuaries* 25: 1275–1290.

Lindeboom H (2002) The coastal zone: An ecosystem under pressure. In: Field JG, Hempel G, and Summerhayes C (eds.) *Oceans 2020: Science, Trends, and the Challenge of Sustainability*, pp. 49–84. Washington, USA: Island Press.

Lloret J, Palomera I, Salat J, and Solé I (2004) Impact of freshwater input and wind on landings of anchovy (Engraulis encrasicolus) and sardine (Sardina pilchardus) in shelf waters surrounding the Ebre River delta (northwestern Mediterranean). *Fisheries Oceanography* 13(2): 102–110.

McLusky DS and Elliott M (2004) *The Estuarine Ecosystem. Ecology, Threats and Management*. Oxford, UK: University Press.

Roelke DL (2000) Copepod food quality threshold as a mechanism influencing phytoplankton succession and accumulation of biomass, and secondary productivity: A modelling study with management implications. *Ecological Modelling* 134: 245–274.

Syvitski JPM, Harvey N, Wolanski E, *et al.* (2005) Dynamics of the coastal zone. In: Crossland CJ, Kremer HH, Lindeboom HJ, *et al.* (eds.) *Coastal Fluxes in the Anthropocene.* Berlin: Springer.

Wolanski E (2001) *Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef*. Boca Raton, FL: CRC Press.

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

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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.