Developments in Ecosystems, volume 1
Edited by M.H. Wong

Chapter 1

A Comparison of Issues and Management Approaches in Moreton Bay, Australia and Chesapeake Bay, USA

W.C. Dennison, T.J.B. Carruthers, J.E. Thomas and P.M. Glibert

University of Maryland, Center for Environmental Science, P.O. Box 775, Cambridge, MD 21613, USA

Abstract. Management of coastal systems is becoming increasingly important, however understanding the process of effective management often remains elusive. This chapter contrasts examples of environmental problems and associated management in Moreton Bay, Australia, and Chesapeake Bay, USA. Targeted research in Moreton Bay identified specific issues which led to changed practices, while intense management and research in Chesapeake Bay has been unable to keep pace with increasing anthropogenic stress. The balance of political, financial and scientific aspects of a management solution is discussed, with global examples. Sustainable solutions to environmental problems in coastal ecosystems will only be achieved with a rigorous approach to management and the development of global standards.

1.1. Introduction

As humans continue to impact coastal ecosystems at a global scale, coastal management can be viewed as a globally significant and important activity (IGBP, 2001). Coastal management can be considered to be the sum total of human interactions within an ecosystem, whether or not these interactions are formalized into a management structure or series of documents. Accepting this assumption, coastal management is a major environmental issue for the globe, involving more people in more ways than many other issues. Management of the coastal zone is typically complicated, involving multiple jurisdictional boundaries and a variety of issues. In most cases, the plethora of human activities are not encompassed into a coastal management structure, rather they evolve around various issues and activities that impinge on coastal management. Thus, coastal management

DOI: 10.1016/S1572-7785(04)01001-9

activities are often not well documented and developing global data sets regarding coastal management issues is difficult. This chapter describes two main case studies in order to draw out the issues of environmental problem solving. These case studies serve to illustrate the point that each environmental problem can benefit from scientific research, and a solution-focused management approach can be developed for each problem in collaboration with the community. The problems, research, and solution-focused management approaches presented for each case study are in no way comprehensive — there are many more problems, more research and more solutions than covered here.

1.2. Comparison of Systems

The two principal case studies are Moreton Bay, Australia, and Chesapeake Bay, USA. In many respects, Moreton Bay is approximately one tenth of Chesapeake Bay (Fig. 1, Table 1). In terms of human population, Moreton Bay has roughly

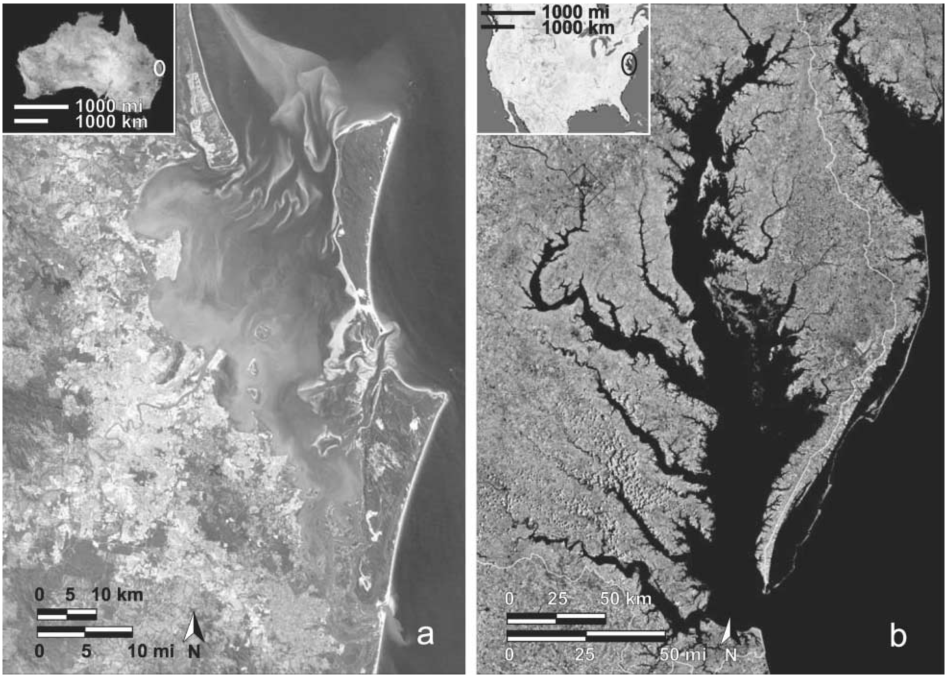

Figure 1: Satellite photographs of (a) Moreton Bay with Australia inset. Images from: Australia, ACRES Landsat 7 Mosaic of Australia, Pseudo Natural Color Image; Moreton Bay, ACRES Landsat 7, 21 March 2003, Natural Color Image and (b) Chesapeake Bay with USA inset. Images from: USA, NASA visible earth; Chesapeake Bay, USGS.

Table 1: Comparison statistics for Moreton Bay and Chesapeake Bay.

	Moreton Bay	**Chesapeake Bay**
Latitude	27° S	38° N
Watershed area	21,220 km^2/8193 $mile^2$	165,800 km^2/64,000 $mile^2$
Bay area	1,523 km^2/588 $mile^2$	18,130 km^2/7000 $mile^2$
Watershed population	Approx. 1.5 million	Approx. 15 million
Average depth	6.8 m/22 ft	6.4 m/21 ft

Data from Dennison & Abal (1999), Horton (2003) and Skinner et al. (1998).

1.5 million people living in its watershed, mostly in the city of Brisbane, while Chesapeake Bay has roughly 15 million people, including the cities of Washington DC, Baltimore, Norfolk and Richmond. In terms of watershed area, the Moreton Bay watershed is $\sim 21{,}000\ km^2$ while Chesapeake Bay is $\sim 165{,}000\ km^2$. In terms of bay area, Moreton Bay is $\sim 1{,}500\ km^2$ and Chesapeake Bay is $\sim 18{,}000\ km^2$ (Skinner et al., 1998; Horton, 2003) (Table 1). Therefore, the ratio of people to bay are roughly proportional in both systems and so, in terms of population pressure and potential anthropogenic effects, Moreton Bay can be viewed as a microcosm of Chesapeake Bay.

Both bays are adjacent to industrialized, urban/suburban developments with a well developed management infrastructure. Both are situated on the east coast of a continent with a warm offshore current, have a mean depth of $\sim 6-7$ m, historically productive fisheries, a fringe of mangrove forest or salt marsh and historically extensive seagrass and oyster reefs. One important difference is that Moreton Bay is subtropical, located at 27° S, while Chesapeake Bay is temperate, located at 37° N.

The balance of environmental concerns differ between Moreton Bay and Chesapeake Bay, with pulsed sediments being the largest issue in Moreton Bay (and nutrients secondarily) while nutrients are the largest issue in Chesapeake Bay (and sediments secondarily) (Fig. 2, Table 2). Moreton Bay has one large connection to the sea, with two smaller entrances, while Chesapeake Bay only has one large sea opening (Fig. 1).

Both systems have been relatively well studied on a global scale. While Moreton Bay has had recent intensive research, Chesapeake Bay has had intensive research historically and recently, making it one of the most studied estuaries in the world (Tibbets et al., 1998; Dennison & Abal, 1999; Ernst, 2003). In both regions, a heightened awareness of bay issues has been developed with the aim of achieving protection and restoration. The development of protection is appropriate for Moreton Bay, while Chesapeake Bay requires a major restoration effort.

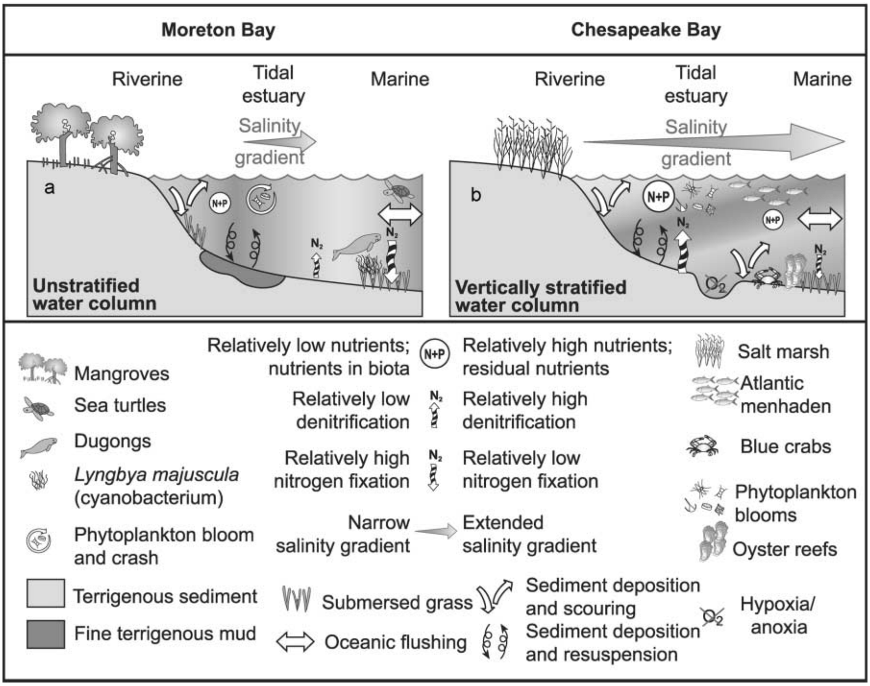

Figure 2: Conceptual diagrams contrasting the major features of (a) Moreton Bay and (b) Chesapeake Bay.

1.3. Moreton Bay Overview

Moreton Bay is fringed with mangroves and has two major rivers discharging into the western bay. The Brisbane and Logan Rivers have watersheds that extend to the Great Dividing Range, west of Brisbane. Rainfall in the Moreton Bay region is intermittent, with short intense rainfall interspersed with long periods of dry conditions. The highest rainfall events are associated with monsoonal depressions during summer (December–February) and sediment inputs occur during these pulsed river flow periods. Thus, the rivers only flow for a short time, and the tidal sections of these river-estuaries act as seawater inlets or coastal embayments for much of the year (Davies & Eyre, 1998; Carruthers et al., 2002). This results in a narrow salinity gradient during the predominant dry periods, extending only tens of kilometers within the river/ estuary. The bay itself retains full strength salinity for most of the year, but during high rainfall periods significant reductions in bay salinity can occur. Moreton Bay experiences a 1.7 m tidal range, and the ensuing mixing combined

Table 2: Examples of environmental problems from Moreton Bay and Chesapeake Bay.

Estuary	**Problem**	**Result**	**Research results**	**Potential solutions**
Moreton Bay	Fine grained sediments	Seagrass loss	Sediment from channel erosion in agricultural regions	Replant and fence eroding channels
	Sewage nutrients	Macroalgal blooms	Sewage plumes mapped	Biological nutrient removal upgrades
	Lyngbya blooms	Human health issues	*Lyngbya* blooms linked to forestry practice	Monitoring and revised forestry practice
Chesapeake Bay	Nutrient addition	Hypoxia/ anoxia	Decomposing phytoplankton lead to oxygen depletion	Reduction of point and diffuse nutrient sources
	Critical habitat loss	Oyster and seagrass loss	There are multiple causes of decline	Oyster restocking and seagrass restoration
	Accelerated erosion	Sedimentation	Shoreline erosion influenced by sea level rise	Augment marshes and islands, e.g. possible use of dredge spoil
	Harmful algal blooms	Fish kills, human health, hypoxia	Nutrients and salinity important, also nutrient interactions	Nutrient reductions, continuous nutrient monitoring

List of problem statement, research findings and management solutions either proposed or enacted.

with the lack of freshwater results in vertically unstratified water masses. In addition, wind driven mixing leads to sediment resuspension in the western margins of the Bay and the water is often brown in color (Longstaff et al., submitted). Low dissolved oxygen conditions are not common in Moreton Bay. Water circulation in the bay is generally in a clockwise direction, with onshore prevailing winds leading to the poorest flushing in the western embayments near the river mouths (Fig. 3a). Nutrients derived from both point and non-point sources are delivered primarily into the western bays and strong horizontal gradients exist for most water quality parameters. The nutrient inputs into Moreton Bay are rapidly assimilated by biota or deposited into sediments, such that water column nutrients in the bay are near detection limits most of the time (O'Donohue et al., 2000). Moreton Bay has an assemblage of tropical seagrass that support a large population of dugong and sea turtles. Recent outbreaks of a harmful algal bloom (*Lyngbya majuscula*) have occurred in this area where there is a large trawl fishery for penaeid shrimp and intensive recreational fishing.

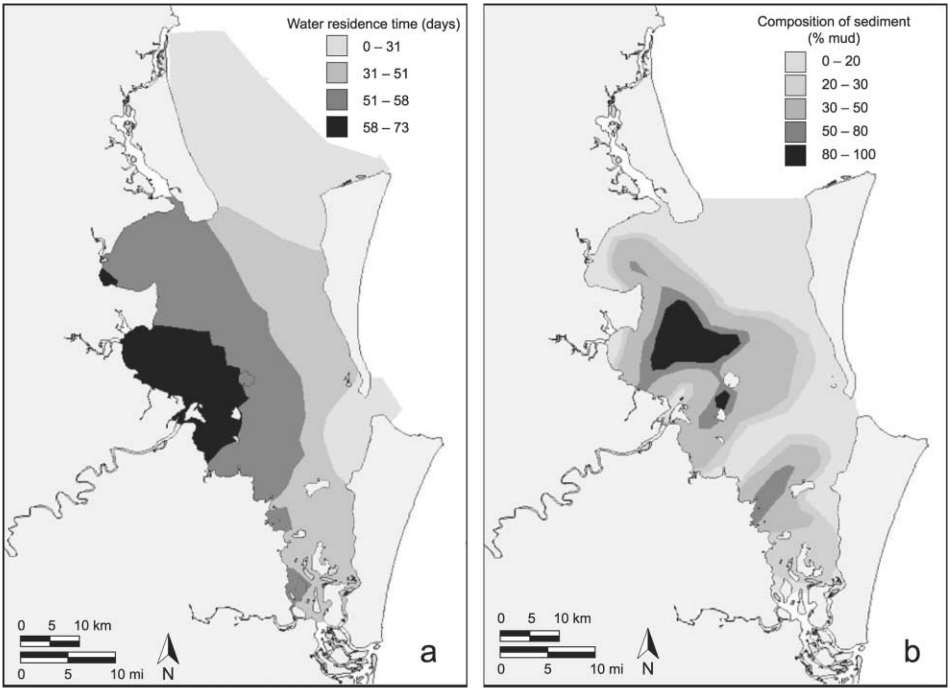

Figure 3: (a) Residence time of water in Moreton Bay Australia, data from Longstaff et al. (2004). (b) Sediment type throughout Moreton Bay, Australia, data from Longstaff et al. (2004).

1.4. Moreton Bay Sediments and Seagrass Loss

Problem The watershed of Moreton Bay is sparsely vegetated (due to clearing for agriculture and urban development) and large rainfall events deliver sediments into the rivers and eventually into the Bay (Table 2). These sediments are largely deposited into the deep (10–20 m) basin in western and central Moreton Bay. The fine grained sediments form mud deposits that are frequently resuspended by the dominant southeast wind in the region (Longstaff et al., submitted) (Fig. 3b). The resuspended sediments increase water turbidity and reduce light penetration. As a result of reduced light penetration, seagrass growth is inhibited (Fig. 4a). Seagrass losses have been observed in the turbid regions of the bay, leading to loss of habitat for juvenile penaeid shrimp as well as loss of grazing areas for turtles and dugong (Abal & Dennison, 1996).

Research Once the problem of seagrass loss was recognized and linked to resuspension of fine-grained sediments, the scientific challenge was to locate

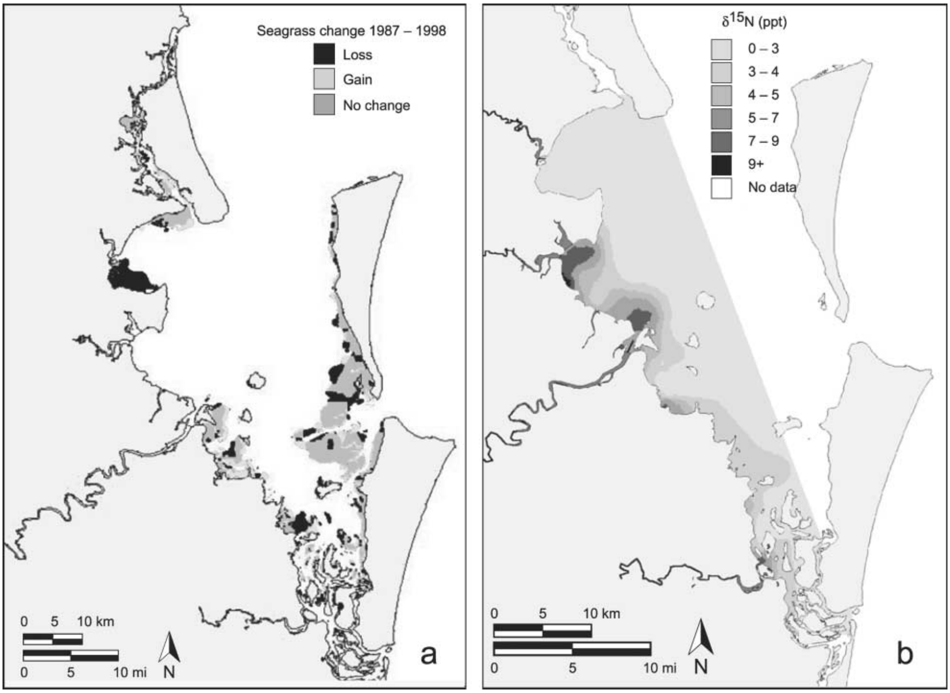

Figure 4: (a) Change in seagrass cover in Moreton Bay between 1987 and 1998, data from Longstaff et al. (submitted). (b) Sewage plume map (δ^{15}N) for Moreton Bay in September 1997. After Costanzo et al. (2001).

the source(s) of these sediments in order to develop control measures. Levels of two geochemical tracers (thorium and lanthium) in Moreton Bay sediments were compared with various soil samples from the watershed. Sediment dating of cores taken from the central mud patch revealed that the fine grained sediments available for resuspension were deposited relatively recently (within the past 90 years). Thus, it was clear that human alterations of the watershed had accelerated natural processes of sedimentation. The sediment source was shown to be confined to subwatersheds of the Brisbane and Logan Rivers. In another set of tracer measurements, the amounts of radium and cesium in sediments of the Brisbane and Logan Rivers were compared with watershed topsoils (cultivated and uncultivated) and subsoil. These results indicated that land disturbance and, in particular, channel erosion was the principle mechanism of soil erosion contributing to Moreton Bay sediments. This channel or gully erosion in the smaller streams was being exacerbated by agricultural fields without riparian buffers next to streams and grazing activities of cattle and sheep which removed riparian vegetation and weakened stream banks.

Working toward a solution Once research had identified the highly erosion susceptible areas in the watershed, as well as the mechanism of erosion, it was possible to initiate a targeted approach for management actions (Table 2). The practical solution was to fence the livestock and prevent grazing activity while revegetating already degraded stream banks. Another important component of the solution was the education of land owners with regard to the linkage between land use and sediment runoff; this was done by community involvement in field trials of riparian revegetation.

1.5. Moreton Bay Sewage Plumes

Problem Nutrients entering Moreton Bay led to large beach wracks of macroalgae ("sea lettuce"-*Ulva* sp.) near the Brisbane River mouth and occasional dinoflagellate blooms in the western embayments (Uwins et al., 1998; Dennison & Abal, 1999) (Table 2). The majority of sewage effluent discharge occurs into the rivers, with 18 major ($>$0.5 ML of effluent per day) treatment plants discharging into the Brisbane and Pine Rivers alone (Dennison & Abal, 1999). Since these rivers are highly turbid and little biological processing of nutrients occurs, the river mouths discharge the bulk of the nutrients into the western bays of Moreton Bay (O'Donohue et al., 2000) (Fig. 4b). The extent and relative proportion of the sewage contribution to this nutrient over-enrichment problem was previously unknown.

Research A technique for tracing sewage plumes was developed using marine plants as biological indicators of nutrient sources. Marine plants readily absorb nutrients for growth and nutrition and the ratio of various naturally occurring isotopes of nitrogen in the plant tissue reflects the ratio in the surrounding water (Wada, 1980; Grice et al., 1996; Udy & Dennison, 1997; Dennison & Abal, 1999; Waldron et al., 2001). The ratio of ^{14}N:^{15}N, relative to an atmospheric standard (calculated as $\delta^{15}N$), is variable and different nitrogen sources have different $\delta^{15}N$ values. Preliminary investigations demonstrated that the $\delta^{15}N$ of a species of red macroalgae (*Catenella nipae*) would reflect the $\delta^{15}N$ signature from sewage nitrogen inputs within several days. The method involves deploying and retrieving several hundred macroalgae in a grid throughout the bay, with the resulting $\delta^{15}N$ values being spatially analyzed and mapped (Costanzo et al., 2000). These maps revealed distinct sewage plumes emanating from high input areas (Costanzo et al., 2001).

Working toward a solution The preparation and dissemination of sewage plume maps using the biological indicator results was an extremely powerful tool for stimulating sewage treatment upgrades in the region (Table 2). These upgrades, staged over several years and costing hundreds of millions of dollars, resulted in dramatic reductions in sewage plume extent and also reduced wracks of *Ulva* sp. in the vicinity of river mouths. Further improvements in sewage treatment technologies and increased wastewater reuse should continue the trend of sewage plume reductions. Reduction of known point sources of nutrients makes non-point nutrient inputs easier to identify and quantify. Reduction of these diffuse sources is the next challenge to solve.

1.6. Moreton Bay Harmful Algal Blooms

Problem Outbreaks of a marine cyanobacterium that caused human and ecosystem health problems began in the 1990s in Moreton Bay (Dennison et al., 1999) (Table 2). Moreton Bay fishermen began complaining of skin lesions as well as throat and eye irritation when an unusual proliferation of filamentous ‘weed’ covered the seagrass. Investigation revealed the presence of *Lyngbya majuscula*, a cyanobacterium with toxins known to cause contact dermatitis (Osborne et al., 2001). During the mid- and late-1990s, *Lyngbya* spread to other regions of the bay, smothering seagrass and mangroves, with large wracks washing up on swimming beaches (Fig. 5). Turtle and dugong populations appeared to be affected, tourism and fish catches have reduced and nitrogen inputs through *Lyngbya* nitrogen fixation may even counteract some of the nitrogen reduction strategies.

Research An intensive research program was initiated to determine the cause(s) of *Lyngbya* initiation and proliferation. Initial results pointed to the availability of dissolved iron as a trigger for this cyanobacterial bloom initiation. Subsequent research into the iron chemistry and runoff from various

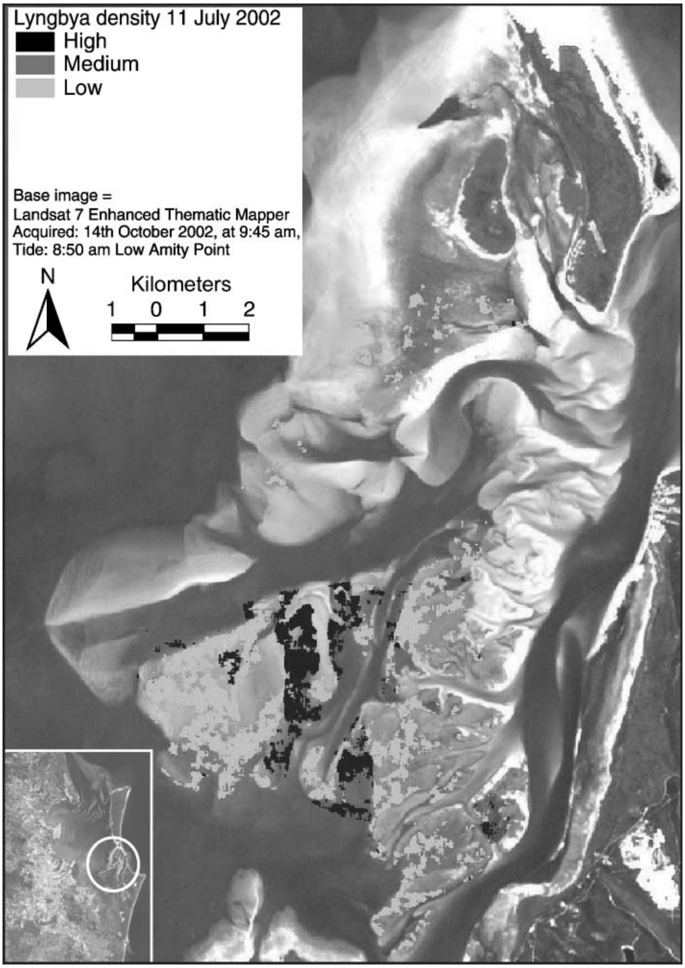

Figure 5: Distribution of *Lynbya majuscula* bloom in Moreton Bay during 2002, Data provided by C. Roelfsema, University of Queensland, Australia 2003.

potential land sources revealed a link between land clearing of plantation pines and runoff of organic-rich water containing dissolved iron and *Lyngbya* blooms. A phase of rapid deforestation in the 1990s due to rotation cycles, economic factors as well as a wildfire event in the pine plantations were hypothesized to result in pulses of organic-stained water into the bloom initiation region. The initial results of dissolved iron and *Lyngbya* stimulation, as well as observations of orange-stained water with high iron levels in the vicinity of canal estates, led to early suspicions that dredging and filling could be stimulating blooms. Eventually, the organic compounds in runoff from pine plantations were found to make the dissolved iron more bioavailable to the cyanobacteria and so this acidic, black water runoff enhanced *Lyngbya* growth rates (Albert, 2001; Rose & Waite, 2003).

Working toward a solution Various mechanical harvesting techniques were trialed, and were largely unsuccessful due to logistic and economic considerations. A moratorium on canal estate construction was discussed, but eventually discounted as runoff from pine plantation deforestation was thought to be the major problem (Table 2). A program involving the forestry industry, in which various trials of forestry practices will test rates of organic and iron-rich runoff was established. A predictive model is currently being developed that will be used to guide future management decisions.

1.7. Chesapeake Bay Overview

Chesapeake Bay is fringed with salt marshes and has several major rivers discharging into the western bay (Potomac, Rappahanok, James, York) that have their origins in the Appalachian Mountains in western Maryland, Virginia and West Virginia. However, the bulk of freshwater inputs are from the Susquehanna River which drains a large section of Pennsylvania and discharges into the northern bay. The salinity gradient is extensive (360 km along the main axis of the bay). Runoff is more or less continuous, forming a distinct salt wedge (Boicourt et al., 1999). Chesapeake Bay was formed as a drowned river valley of the Susquehanna River and low oxygen conditions occur in bottom waters, particularly in the deep trough formed from this historical valley. Chesapeake Bay has a minimal astronomical tidal range (<0.5 m), but meteorological tides due to weather patterns contribute to mixing. Water circulation in the bay is largely driven by the freshwater inflows with seawater extending further up the eastern shore due to the Coriolis force. Nutrients derived from both point and non-point sources are delivered throughout the bay, with predictions that agriculture inputs constitute 55.2% and sewage 20.7% of nitrogen export from the watershed into Chesapeake Bay (Boynton et al., 1995; Castro & Driscoll, 2002). As a result, up to 27% of Chesapeake Bay has been classified as eutrophic (Kiddon et al., 2003). Phytoplankton blooms are common, including some toxic species. Residual nutrients remain in the water column throughout the bay for most of the year. Chesapeake Bay has an assemblage of freshwater and marine submersed grasses that support large waterfowl populations. There is a large crab, anchovy and menhaden fishery and intensive recreational fishing. Historically, there was a fishery based on the abundant anadromous shad and a massive oyster fishery.

1.8. Chesapeake Bay Nutrient Over-Enrichment

Problem A major problem in Chesapeake Bay is the development of summertime low dissolved oxygen in bottom waters, particularly in the deep basins (Table 2). While increased land clearing was related to increased hypoxia between 1700 and 1900, the advent of fertilizer use during the 20th century has led to unprecedented anoxic events since the 1970s (Cronin & Vann, 2003) (Fig. 6). This hypoxia (low oxygen) or anoxia (no oxygen) is detrimental to benthic organisms, including a reduction in oyster (*Crassostrea virginica*) growth rates (Widdows et al., 1989). In addition, anoxic bottom waters facilitate the release of sediment nutrients, particularly phosphorus and ammonium, mobilizing nutrients that would otherwise be locked up in sediments. The morphology of the bay and the naturally stratified water column results in a natural tendency for low oxygen in bottom waters. What has developed into a problem is the increase in severity, extent and persistence of the low oxygen events. The volume of bay water affected by hypoxia (dissolved oxygen $<2\,\mathrm{mg\,l^{-1}}$) has been steadily increasing since the 1950s (Cronin & Vann, 2003). In wet years (e.g. 1998), the

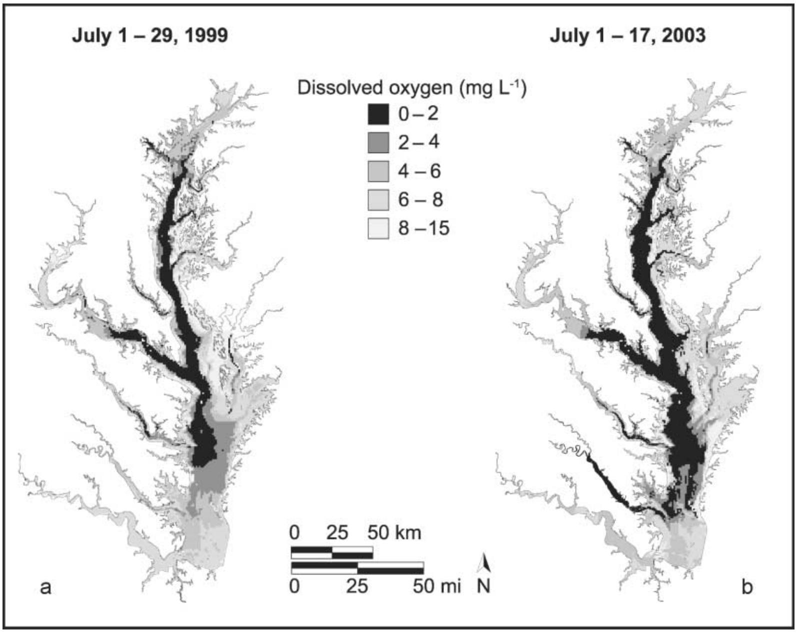

Figure 6: Dissolved Oxygen in Chesapeake Bay in (a) July 1999 (a standard year) and (b) July 2003 (a high rainfall year). Data provided by Chesapeake Bay Program.

hypoxic and anoxic waters threaten not only the deep basins, but also the more shallow regions.

Research Low oxygen bottom waters have been linked to the growth and subsequent decay of phytoplankton (Kemp et al., 1992). Phytoplankton growth is stimulated by nutrient inputs, particularly the winter/spring runoff that leads to a spring bloom of diatoms (Anderson et al., 2002). The microbial decay of diatoms as they settle to the bottom consumes oxygen faster than it can be replenished by diffusion and advection from the surface, leading to hypoxia and anoxia. A variety of measurements and models have been developed with relatively good predictive capacity. Even a basic model using only two variables to predict the hypoxic volume of the bay can be effective. The product of total nitrogen concentration and river flow at the tidal limit has been used successfully to predict hypoxic volume (Hagy, 2002).

Working toward a solution The reduction of nutrient point sources mandated throughout a multi-jurisdictional agreement (Chesapeake Bay Agreements of 1987 and 2000), has resulted in nutrient reductions in some locations. For example, the Patuxent River nutrient concentrations dating back to 1960 have been monitored, with significant reductions occurring as a result of sewage treatment upgrades (Table 2). These nutrient reductions are largely associated with western shore urban regions, while agricultural regions of the eastern shore showed significant increase in nutrient export between 1985 and 1995 (Glibert & Magnien, 2004). What the Patuxent River data demonstrates is that local government and community partnerships can accomplish real reductions in nutrient inputs. However, the broader problems of various diffuse sources including atmospheric inputs, agricultural runoff and septic inputs to Chesapeake Bay are showing no signs of abating.

1.9. Chesapeake Bay Critical Habitat Loss

Problems Historically, Chesapeake Bay supported extensive oyster reefs (Table 2). These reefs were built up from layers of dead oyster shells, with a top layer of live oysters. The reefs provided habitat for various attached organisms as well as a place for fish to congregate. The bay also supported vast meadows of submersed aquatic plants-extending from marine salinities to the fresh water river reaches. These aquatic grass beds provided habitat for juvenile fishes and invertebrates as well as food for some waterfowl (e.g. canvasback ducks). Over the last 30–40 years oyster populations have reduced to only 1% of historical abundance in the Chesapeake, while aquatic grasses occupy less than 10% or their historic distribution (Fig. 7a) (Rothschild et al., 1994; Boynton et al., 1996; Orth et al., 2002).

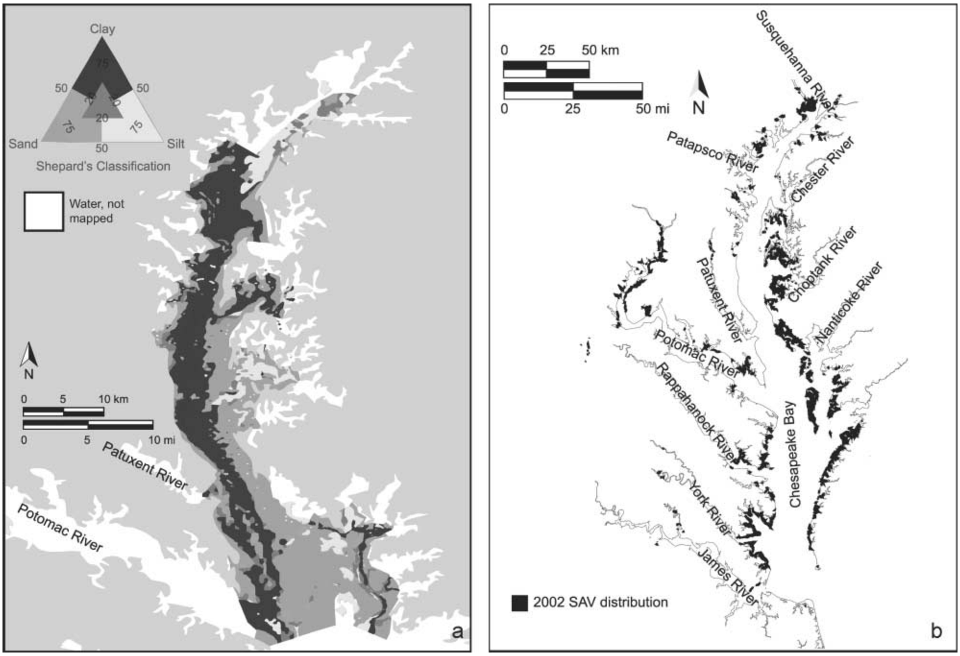

Figure 7: (a) Submersed grass (SAV) distribution in Chesapeake Bay. Data provided by Dave Wilcox, VIMS SAV lab and (b) Sediment type distribution in Chesapeake Bay. Image adapted from *Surficial Sediments of Chesapeake Bay, Maryland: Physical Characteristics and Sediment Budget* Kerhin, R. T. et al., 1988. Maryland Geological Survey.

Research Various studies conducted over three decades have explored the causes of the disappearance of oysters and submersed grasses. The decline in oyster numbers has been linked to overfishing, pollution and disease, while the disappearance of aquatic grasses has been linked to light reductions from eutrophication and turbidity (Dennison et al., 1993; Ernst, 2003). Associated research has also elucidated the critical role that filtration by oysters played in the ecology of the bay, including removing phytoplankton and particulate matter from the water column and enhancing denitrification in shallow water (Newell, 1988). Similarly, aquatic grass beds played a key role in reducing water movement and hence trapping and binding of suspended sediments (Fonseca et al., 1982). Continuing research is assessing all aspects of habitat requirements for potential re-establishment of aquatic grass in the bay (Koch, 2001).

Working toward a solution The elucidation of the key ecological roles of oysters and aquatic grasses has led to oyster restocking and seagrass restoration programs (Table 2). Large scale oyster hatcheries and aquatic grass nurseries have been built, and replanting programs developed. These have been partially supported by volunteer networks. Introduction of an exotic oyster species with disease resistance is being contemplated. There are significant caveats associated with these restoration programs: degraded water quality and/or degraded habitat reduce the likelihood of survival of oyster spat and aquatic grass propagules. Another difficulty is that direct restoration is typically both very expensive and highly labor intensive.

1.10. Chesapeake Bay Sedimentation

Problem Chesapeake Bay is a natural sedimentation basin, and on a geologic time scale is steadily filling in (Fig. 7b). Rates of sedimentation have been accelerated due to land use changes (e.g. increasing agriculture) leading to runoff and deposition, as well as sea level rise and resultant coastal erosion (Table 2). The major Susquehanna River dam (Conowingo dam) is rapidly filling with sediment and is predicted to reach nutrient and sediment capacity in less than 15 years (Langland, 1998). Further upstream on the Susquehanna River, the Safe Harbor and Holtwood Dams have already reached their capacity for storing nutrients and sediment (Langland, 1998). Once the Conowingo dam is full, the mean annual sediment load to Chesapeake Bay will increase by 250% and the phosphorus load by 70% (Langland & Hainly, 1997). The deep water approaches to Baltimore Harbor currently require annual dredging to remain navigable. Currently, the dredge spoil from this navigation dredging is being relocated to a couple of artificially constructed islands in the bay.

Research The role of sedimentation in the bay has been elucidated through a variety of research approaches. It is now realized that the interplay between relative sea level rise and shoreline processes has a large influence upon sediment dynamics. Chesapeake Bay is a region of rapid relative sea level rise (30 cm in the last 100 years, nearly twice the global average), contributing to extensive salt marsh erosion, with several low islands already drowned (Stevenson & Kearney, 1996). Groundwater extraction, principally for agriculture, results in land subsidence and therefore further accelerates relative sea level rise (Davis, 1985).

Working toward a solution Various incentive schemes have been devised for farmers to maintain cover crops during the period of the year when the fields are fallow, to aid in reducing erosion and sediment deposition to the bay (Table 2). A scheme for using dredge spoil to augment the marshes and islands that are eroding is being explored. This could alleviate the problem of dredge disposal as well as preserving salt marsh habitat.

1.11. Chesapeake Bay Harmful Algal Blooms

Problem Harmful algal blooms in Chesapeake Bay are increasing in frequency and diversity (Glibert & Magnien, in press) (Table 2). This has been related to increased nutrients entering the estuary, the major sources being fertilizer, manure, atmospheric deposition and sewage (Glibert & Magnien, in press). There are two main detrimental effects of these blooms; firstly, the direct effect of the toxins upon humans and bay fauna and secondly, hypoxia or even anoxia in bay waters (Table 3). Species such as *Pfiesteria piscicida*, *Microcystis aeruginosa* and *Dinophysis* sp. have been linked to human health issues, with blooms resulting in river closures. The anoxia associated with large decaying blooms of *Prorocentrum minimum* have caused fish and shellfish stress and death (Table 3; Glibert & Magnien, in press).

Research The harmful algal bloom species that occur in Chesapeake Bay are very diverse, from the dinoflagellate *P. piscicida* with a complex life cycle to the nitrogen fixing cyanobacteria *M. aeruginosa*. As a result the specific triggers of blooms can be more complex than simply the presence of higher nutrient concentrations. As well as diverse research into physiology, grazing, population dynamics and triggers to toxin production, continued research employing continuous in situ nutrient sensors is helping to elucidate the interactions of nutrient pulses and salinity as well as the effects of nutrient ratios (nitrogen: phosphorus: silicon) and how these balances may control both the species and intensity of harmful algal blooms (Table 3) (Glibert & Magnien, in press).

Working toward a solution Harmful algal blooms have implications for political, medical and scientific communities, therefore the solution must encompass all these groups. To this end, a task force has been established between State of Maryland agencies and the medical community to address

Table 3: Common Harmful Algal Bloom (HAB) species in Chesapeake Bay, with major impacts and causes.

Algal species	**Toxic effects**	**Causes hypoxia**	**Probable bloom cause**
Pfiesteria piscicida	Yes	No	Nutrients, other algal blooms
Prorocentrum minimum	No (?)	Yes	Freshwater, nutrients
Microcystis aeruginosa	Yes	No	Nutrients (phosphorus)
Dinophysis sp.	(?)	No	High salinity, nutrients

After Glibert & Magnien (in press).

specific issues and recommend river closures where required. In the Potomac River, phosphate removal from sewage has been effective in reducing 70 μg l^{-1} blooms of *Microcystis* spp to populations generally less than 20 μg l^{-1} (Anderson et al., 2002). The general issue of nutrient inputs to Chesapeake Bay is a continuing problem. However, in areas where point sources were the primary concern, some reductions in nutrient loads have been achieved with resultant reduction in harmful algal blooms in these areas (Anderson et al., 2002; Glibert & Magnien, in press).

1.12. Overcoming Challenges

There are political, financial and scientific challenges to be overcome in addressing environmental problems. Drawing upon case studies presented at the International Riverfestival held in Brisbane (Australia) over the past several years, examples of programs that have overcome some of these challenges will be discussed. Only when all three aspects of the challenges have been addressed can a solution be achieved and in every separate case the relative difficulty of the three aspects of the environmental problem varied due to historical and site specific factors.

The physical size of the system also influences the difficulty of the political, financial and scientific challenges. The challenges in a larger system (such as Chesapeake Bay) will often have a greater complexity of challenge in finding environmental solutions, simply due to the watershed and airshed having a greater diversity of anthropogenic activity within its boundaries. The Mersey Basin (United Kingdom) is relatively small and defined, so the scientific issues were relatively simple-whereas in the Mekong River (SE Asia), the massive size of the system meant that the political challenges just to coordinate a management effort were enormous.

1.13. Healthy Waterways Campaign Overcomes Population Growth

The challenge that *population growth counteracts any progress made with management interventions* is one that most coastal watersheds face as both population growth and coastal migration have led to increased human population impacts in coastal regions. Moreton Bay is in the region of largest population growth in Australia, so the primary issue in working towards a solution for environmental problems was political. The response to this challenge was a proactive program which accounted for population growth and new development. The result was a plan to manage population growth while maintaining ecosystem health. The Healthy Waterways Campaign in south-east Queensland, Australia, has achieved water quality improvements in spite of being the fastest growing urban area of Australia, and one of the fastest growing areas of the world (Abal et al., 2001). A key aspect of this program is that it incorporates the entire watershed, and largely encompasses the ecological footprint of the city of Brisbane (water storages, farm land, recreational areas, suburban and urban regions). As a result, population growth and its consequences in terms of services required throughout the region are considered in working towards solving the environmental problems (http://www.healthywaterways.env.qld.gov.au).

1.14. Chesapeake Bay Blues

Chesapeake Bay is the biggest estuary in the USA and significant progress has been made in terms of political (well established management), financial (well supported) and biological (well studied) aspects of solving the environmental problems, however, the Bay is still not improving. The term *Chesapeake Bay Blues* was coined by one of three recent publications, all recognizing that despite 20 years of active effort to improve the health of Chesapeake Bay, the biggest issues of nutrient loading, habitat loss, increased sedimentation and harmful algal blooms remain or have worsened (Boesch & Greer, 2003; Ernst, 2003; Horton, 2003). The continued research and management of Chesapeake Bay over the past 30 years has seen an enormous increase in the understanding of processes within the bay. Small regions have shown some positive signs resulting from reduced sewage inputs (Boynton et al., 1996). Other improvements include increases in striped bass and Atlantic croaker populations. Overall, however, Chesapeake Bay is languishing in a state which has large anoxic events, oyster and seagrass decline, coastal erosion, fish kills and water unsafe for swimming (Ernst, 2003). As early as the 1930s the key issues of sewage inputs, over-harvesting and sediment inputs had been identified, but state boundaries and political forces have hindered significant improvement within the bay (Ernst, 2003). If recent trends continue, it is expected that nutrient loads will increase and air quality will degrade, forest cover will decline, residential sprawl will continue to expand and aquatic grasses and fisheries will decline further (Boesch & Greer, 2003). To move forward, stronger links between political, financial and scientific elements are required. A better balance between research, management and monitoring, focused on effective feedback, will be required to implement established goals and solve the environmental challenges currently facing the bay (Orth et al., 2002; Boesch & Greer, 2003; Dennison, in press; Glibert & Magnien, in press).

In Moreton Bay, the political issues of planning for increased population growth have been able to generate funds and target scientific understanding which has led to significant gains in solving the currently known environmental problems in the bay. In Chesapeake Bay, significant gains in management structure and goal setting, funding and scientific understanding have not resulted in significant gains to the main environmental problems currently known. The Chesapeake Bay community now has the resources to move forward on the often difficult problems such as diffuse agricultural and atmospheric nutrient inputs. If effective, this process can be an example for coastal systems throughout the world. Different systems are at different stages of the process of solving their environmental problems. One exemplary case is the Mersey Basin in the United Kingdom, which solved their issues of point source nutrient pollution, while the Mekong River is succeeding in overcoming significant political issues to establish a management framework for their restoration efforts (http://www.chesapeakebay.net).

1.15. Mersey Basin Campaign Overcomes Cost Considerations

The challenge that *It will cost too much* is one that practitioners around the world are facing, in the Mersey Basin the political solution was present and the biological solution was relatively simple, excessive point source nutrient inputs. The issue of funding can be manifested in a variety of ways, but often represents the single largest challenge. The appropriate response to this challenge is that investments in protection and restoration are cheaper now than they will ever be in the future, and these investments can stimulate local economies. The Mersey Basin Campaign is a 25 year campaign in the world's first industrialized region of NW England. The Mersey basin has two large cities, Liverpool and Manchester, with six million inhabitants. The Mersey River was highly polluted with raw sewage discharges as recently as the 1980s. The land values along the river's edge were actually negative-local government was unsuccessful in giving land away to developers even with a cash incentive. However, a concerted clean-up effort has made the water safe for swimming, and the negative land values are now positive, including the development of a five star hotel on the banks of the river. The Mersey Basin Campaign was the first recipient of the International Riverprize in 1999 (http://www.merseybasin.org.uk).

1.16. Mekong River Commission Overcomes Jurisdictional Issues

A significant initial stage in reaching a solution to environmental problems is to overcome diverse political requirements and priorities. The challenge that *There* *are too many different jurisdictions and stakeholders with divergent views* is one that most regional scale programs face. Coastal watersheds tend to cross jurisdictional boundaries and there are certain to be stakeholders with divergent views in any region. The response to this challenge is that a participatory process can create a shared vision among a variety of stakeholders. The Mekong River Commission has put together a multi-national program involving Cambodia, Lao PDR, Thailand and Vietnam, with links to China. These are countries that have been involved in bitter conflicts with each other within this present generation. The Mekong is the 8th largest river system (in water volume) globally and supports major fisheries. There are 17 million people and 70 ethnic minorities in the Mekong watershed. The Mekong River Commission was the 2002 recipient of the International Riverprize, based on their proven ability to develop a participatory process among their stakeholders (http://www.mrcmekong.org/).

1.17. Conclusions

In many ways, these coastal management programs can be viewed as 'experiments'. While not having replication or controls, the challenge for science practitioners is to apply rigor to these coastal management case studies to develop global standards and work towards more effective management practices. The global trend for increasing human pressures on coastal regions has created a suite of difficult, but tractable environmental problems. Obtaining sustainable solutions to important environmental problems needs to be a major scientific focus of the next half century. The presented case studies of coastal ecosystem management programs serve to introduce environmental problems that are not unique to one region and demonstrate that solutions are possible for a wide variety of problems.

Acknowledgements

This chapter represents outcomes from a series of discussions over the past several years with various different groups of scientists. The case study examples touch on research results from a plethora of scientists. The attempt here will be to acknowledge the programs and groups, and cite some of the key individuals but not provide a comprehensive listing. The Moreton Bay case study was developed as part of the Healthy Waterways Campaign team, in particular Eva Abal, Paul Greenfield and colleagues in the University of Queensland Marine Botany group. The Chesapeake Bay case study was developed with colleagues at the University of Maryland Center for Environmental Science (UMCES), in particular, Donald Boesch, Walter Boynton and Dave Nemazie. Assistance with graphics and editing was provided by Tracey Saxby, Adrian Jones, Ben Longstaff and Chris Roelfsema. Support from the Integration and Application Network, UMCES is acknowledged. UMCES contribution number 3753.

References

Abal, E. G., & Dennison, W. C. (1996). Seagrass depth range and water quality in southern Moreton Bay, Queensland, Australia. *Journal of Marine and Freshwater Research*, **47**, 763–771.

Abal, E. G., Dennison, W. C., & Greenfield, P. G. (2001). Managing the Brisbane River and Moreton Bay: an integrated research/management program to reduce impacts on an Australian estuary. *Water Science and Technology*, **9**, 57–70.

Albert, S. (2001). *The effect of soil extracts on the physiology of Lyngbya majuscula (Cyanophyta)*, Honours thesis. Environmental science. University of Queensland, Brisbane, Australia.

Anderson, D. M., Glibert, P. M., & Burkholder, J. M. (2002). Harmful algal blooms and eutrophication: nutrient sources, composition and consequences. *Estuaries*, **25** (4B), 704–726.

Boesch, D.F., & Greer, J. (Eds.) (2003). Chesapeake futures: choices for the 21st Century. An Independent Report by the Scientific and Technical Advisory Committee. Chesapeake Research Consortium. Chesapeake Bay Program, 160 p.

Boicourt, W. C., Kuzmic, M., & Hopkins, T. S. (1999). The inland sea: circulation of Chesapeake Bay and the Northern Adriatic. In: T. C. Malone, A. Malej, L. W. Harding Jr., N. Smodlaka, & R. E. Turner (Eds), *Coastal and Estuarine Studies 55: Ecosystems at the land–Sea Margin — Drainage Basin to Coastal Sea* (pp. 81–129). American Geophysical Union, Washington DC.

Boynton, W. R., Garber, J. H., Summers, R., & Kemp, W. M. (1995). Inputs, transformations and transport of nitrogen and phosphorus in Chesapeake Bay and selected tributaries. *Estuaries*, **18**, 1B, 285–314.

Boynton, W. R., Hagy, J. D., Murray, L., Stokes, C., & Kemp, W. M. (1996). A comparative analysis of eutrophication patterns in a temperate coastal lagoon. *Estuaries*, **19**, 2B, 408–421.

Carruthers, T. J. B., Dennison, W. C., Longstaff, B. J., Waycott, M., Abal, E. G., McKenzie, L. J., & Lee Long, W. J. (2002). Seagrass habitats of northeast Australia: models of key processes and controls. *Bulletin of Marine Science*, **71**, 3, 1153–1169.

Castro, M. S., & Driscoll, C. T. (2002). Atmospheric nitrogen deposition to estuaries in the mid-Atlantic and northeastern United States. *Environmental Science and Technology*, **36**, 3242–3249.

Costanzo, S. D., O'Donohue, J., & Dennison, W. C. (2000). *Gracilaria edulis* (Rhodophyta) as a biological indicator of pulsed nutrients in oligotrophic waters. *Journal of Phycology*, **736**, 680–685.

Costanzo, S. D., O'Donohue, M. J., Dennison, M. J., Loneragan, N. R., & Thomas, M. (2001). A new approach for detecting and mapping sewage impacts. *Marine Pollution Bulletin*, **42**, 2, 149–156.

Cronin, T. M., & Vann, C. D. (2003). The sedimentary record of climatic and anthropogenic influence on the Patuxent estuary and Chesapeake Bay ecosystems. *Estuaries*, **26**, 2A, 196–209.

Davies, P. L., & Eyre, B. D. (1998). Nutrients and suspended sediment input to Moreton Bay — the role of episodic events and estuarine processes. In: I. R. Tibbets, N. J. Hall, & W. C. Dennison (Eds), *Moreton Bay and Catchment* (pp. 545–552). School of Marine Science, The University of Queensland, Brisbane.

Davis, G. H. (1985). Land subsidence and sea level rise on the Atlantic Coastal Plain of the United States. *Environmental Geology and Water Science*, **10**, 67–80.

Dennison, W. C. (2004). Environmental problem solving in coastal ecosystems: needs and approaches. *Water Science and Technology*, submitted.

Dennison, W. C., & Abal, E. G. (1999). Moreton Bay study: a scientific basis for the healthy waterways campaign. *South East Queensland Regional Water Quality Management Strategy*, 167 p.

Dennison, W. C., Orth, R. J., Moore, K. A., Stevenson, J. C., Carter, V., Kollar, S., Bergstrom, P. W., & Batiuk, R. A. (1993). Assessing water quality with submersed aquatic vegetation. *Bioscience*, **43**, 2, 86–94.

Dennison, W. C., O'neil, J. M., Duffy, E. J., Oliver, P. E., & Shaw, G. R. (1999). Blooms of the cyanobacterium *Lyngbya majuscula* in coastal waters of Queensland, Australia. *Bulletin de l'institut oceanographique, Monaco*, **19**, 501–506.

Ernst, H. R. (2003). *Chesapeake Bay Blues: science, politics, and the struggle to save the bay*. Rowman and Littlefield Publishers Inc, Oxford, 203 p.

Fonseca, M. S., Fisher, J. S., Zieman, J. C., & Thayer, G. W. (1982). Influence of the seagrass, *Zostera marina* L., on current flow. *Estuarine Coastal and Shelf Science*, **15**, 351–364.

Glibert, P. M., & Magnien, R. E. (2004). Harmful algal blooms in the Chesapeake Bay, USA: Common species, relationships to nutrient loading, management approaches, successes, and challenges. In: S. Hall, Z. Mingyuan, Z. Yinglin & L. Cheong (Eds), *Proceedings of the Second International Conference on Harmful Algae Mitigation and Management IOC*. In press.

Grice, A. M., Loneragan, N. R., & Dennison, W. C. (1996). Light intensity and the interactions between physiology, morphology and stable isotope ratios in five species of seagrass. *Journal of Experimental Marine Biology and Ecology*, **195**, 91–110.

Hagy, J.D. (2002). *Eutrophication, hypoxia and trophic transfer efficiency in Chesapeake Bay*. Ph.D. Dissertation. MEES. University of Maryland.

Horton, T. (2003). *Turning the tide: saving the Chesapeake Bay*. Chesapeake Bay Foundation, 386 p.

IGBP. (2001). Global change and the earth system: a planet under pressure. IGBP Science No. 4, 32. *International Geosphere-Biosphere Programme*, Stockholm, Sweden.

Kemp, W. M., Sampou, P. A., Garber, J., Tuttle, J., & Boynton, W. R. (1992). Seasonal depletion of oxygen from bottom waters of Chesapeake Bay — roles of benthic and planktonic respiration and physical exchange processes. *Marine Ecology Progress Series*, **85**, 1–2, 137–152.

Kiddon, J. A., Paul, J. F., Buffum, H. W., Strobel, C. S., Hale, S. S., Cobb, D., & Brown, B. S. (2003). Ecological condition of US mid-atlantic estuaries, 1997–1998. *Marine Pollution Bulletin*, **46**, 1224–1244.

Koch, E. W. (2001). Beyond light: physical, geological, and geochemical parameters as possible submersed aquatic vegetation habitat requirements. *Estuaries*, **24**, 1, 1–17.

Langland, M. J. (1998). Change in sediment and nutrient storage in three reservoirs in the lower Susquehanna River basin and implications for the Chesapeake Bay. USGS fact sheet 003-98.

Langland, M. J., & Hainly, R. A. (1997). Changes in bottom surface-elevations in three reservoirs on the Lower Susquehanna River, Pennsylvania and Maryland, following the January 1996 flood — Implications for nutrient and sediment loads to Chesapeake Bay: U.S. *Geological Survey Water-Resources Investigations Report 97-4138*, 34 p.

Longstaff, B. J., Carruthers, T. J. B., Dennison, W. C., Udy, N., & Udy, J. (2004) The influence of sediment resuspension on seagrass distribution in Moreton Bay, Australia. *Marine and Freshwater Research*, submitted.

Newell, R. I. E. (1988). Ecological changes in Chesapeake Bay: are they the result of overharvesting the American Oyster, Crassostrea virginica? *Understanding the estuary: advances in Chesapeake Bay research. Proceedings of a Conference*. Chesapeake Research Consortium Publication 129, Baltimore, Maryland, pp. 29–31, CBP/TRS 24/88.

O'Donohue, M. J., Glibert, P. M., & Dennison, W. C. (2000). Utilization of nitrogen and carbon by phytoplankton in Moreton Bay, Australia. *Marine and Freshwater Research*, **51**, 7, 703–712.

Orth, R. J., Batiuk, R. A., Bergstrom, P. W., & Moore, K. A. (2002). Regulations influencing the protection and restoration of submerged aquatic vegetation in Chesapeake Bay, USA. *Bulletin of Marine Science*, **71**, 3, 1391–1403.

Osborne, N. J. T., Webb, P. M., & Shaw, G. R. (2001). The toxins of *Lyngbya majuscula* and their human and ecological health effects. *Environment International*, **27**, 5, 381–392.

Rose, A. L., & Waite, T. D. (2003). Kinetics of iron complexation by dissolved natural organic matter in estuarine waters. *Marine Chemistry*, **84**, 85–103.

Rothschild, B. J., Ault, J. S., Goulletquer, P., & Heral, M. (1994). Decline of the Chesapeake Bay oyster population — a century of habitat destruction and overfishing. *Marine Ecology Progress Series*, **111**, 1-2, 29–39.

Skinner, J. L., Gillam, E., & Rohlin, C. J. (1998). The demographic future of the Moreton Region. In: I. R. Tibbetts, N. J. Hall, & W. C. Dennison (Eds), *Moreton Bay and Catchment*. School of Marine Science, The University of Queensland, 645 p.

Stevenson, C. J., & Kearney, M. S. (1996). Shoreline dynamics on the windward and leeward shores of a large temperate estuary. In: K. F. Nordstrom, & C. T. Roman (Eds), *Estuarine Systems: Evolution, Environments and Human Alterations* (pp. 233–258).

Tibbetts, I. R., Hall, N. J., & Dennison, W. C. (Eds) (1998). *Moreton Bay and Catchment*. School of Marine Science, The University of Queensland, 645 p.

Udy, J. W., & Dennison, W. C. (1997). Physiological responses of seagrasses used to identify anthropogenic nutrient inputs. *Marine and Freshwater Research*, **48**, 605–614.

Uwins, P. J. R., Yago, A. J. E., Yago, J. V. R., & Quicio, M. (1998). Baseline monitoring of the phytoplankton and phytoplankton Bloom associations in the Southern Moreton Bay catchment. In: I. R. Tibbets, N. J. Hall, & W. C. Dennison (Eds), *Moreton Bay and catchment* (pp. 309–318). School of Marine Science, The University of Queensland, Brisbane.

Wada, E. (1980). Nitrogen isotope fractionation and its significance in biogeochemical processes occurring in marine environments. In: E. D. Goldberg, & Y. Horibe (Eds), *Isotope marine chemistry* (pp. 375–398). Uchida-Rokakuho.

Waldron, S., Tatner, P., Jack, I., & Arnott, C. (2001). The impact of sewage discharge in a marine embayment: a stable isotope reconnaissance. *Estuarine, coastal and shelf science*, **52**, 111–115.

Widdows, J., Newell, R. I. E., & Mann, R. (1989). Effects of hypoxia and anoxia on survival, energy-metabolism and feeding of oyster larvae (*Crassostrea virginica*, Gmelin). *Biological Bulletin*, **177**, 1, 154–166.