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The rising tide: combating coastal pollution

Coastal zones are major hubs for economic and social activity and are in the front line of climate change. To safeguard these fragile ecosystems for our own and future generations we have to move towards more integrated approaches to the assessment and management of coastal and marine environments. Environmental monitoring—broadly defined—has a huge role to play.

Coasts, the border line where the land meets the sea, occupy a unique place in the human imagination. As well as being places of immense beauty, coastal regions are of huge economic importance, either as fishing grounds, ports or sites for industry, and in more recent times have become recreational havens and a source for tourism.

It is not by chance that virtually all of the world's major cities are located on coasts. An estimated 50% of the world's population live within coastal regions and in some countries their importance is even more pronounced. In the United States, for example, over 50% of the population lives within 70 kilometres of the coastline, with coastal regions being among the fastest growing in the US.[1] In Australia, a quarter of the population lives within three kilometres of the sea and two-thirds reside in coastal towns and cities.[2] Coastal zones are important to developing countries too—as the recent tsunami in Asia demonstrated all too well.

It is precisely because of this concentration of economic and social activity, and also because of their unique nature, that coastal zones are under threat. Population pressure brings with it increased development, agriculture and aquaculture. Such activities can have devastating effects on fragile coastal ecosystems, impacts which are compounded by overfishing and destructive trawling techniques. Overall around one-third of the world's coasts are estimated to be at high risk of degradation.

Coastal ecosystems

The coast is not one ecosystem but several, each with its own distinguishing characteristics and stressors.[3]

Estuaries form one such ecosystem: semi-enclosed bodies of water where fresh water and ocean tide connect such as rivers, lakes, and shorelines. Estuaries provide food, breeding grounds, and habitats to a variety of endangered plants and species. Unlike other coastal systems in terms of nutrients, water levels, and temperatures, estuaries are among the most productive environments supporting commercial fisheries around the world and often are also economic hubs.

Coral reef ecosystems are found in both cold and tropical waters and are among the most diverse and productive communities on Earth.[3,4] They enhance biological diversity, fisheries, tourism, maritime and cultural heritage, and protect shorelines from storm damage. Stressed by human activities and extreme natural events, coral reefs are in decline worldwide. Excess nutrients and sediments, overfishing, coastal development, and increased coral bleaching threaten nearly 60 percent of the world's reefs and the resources they support.

Finally, the coastal ocean encompasses a broad range of saltwater ecosystems, including coral reefs, rocky shores, gravel shores, sandy shores, mud flats, sea grasses, marshes and mangrove forests.[3,5] These ecosystems exist where streams and rivers meet the sea and where tides and coastal currents mix. They are a rich source of commercial fishing and shellfish, and provide many recreational opportunities.

The discussion here focuses primarily on these coastal ecosystems rather than the open ocean, which has its own characteristics and dynamics.

Coastal stressors

The health of marine and estuarine ecosystems is inextricably linked to the catchments with which they interact. Pollution from land-based activities can have a significant effect on coastal environments. Over the last thirty years developed countries have reduced industrial and chemical pollution from point sources substantially. But tackling the more pervasive non-point sources—runoff from major urban areas and agricultural fields—has proven more difficult. Consequently, non-point sources, in particular nutrients and sediment loads, constitute the main concerns for coastal pollution.[6]

Nutrient pollution, or over-enrichment, is a well known problem in freshwater systems. In recent years, scientists have become increasingly concerned about eutrophic conditions in estuarine and coastal systems as well.[7,8] Elevated loads of nutrients—nitrogen and phosphorus—can result in algal blooms, which in turn may adversely impact coastal waters by preventing light reaching benthic plants, and by producing toxins detrimental to animal and human health (see Box 1). Further, the death and decay of algal blooms can reduce the amount of dissolved oxygen available to aquatic life, sometimes causing extensive fish kills.

The discharge of sediments to coastal waters is significantly increased through land clearing, poor cultivation practices and urban development.[2,3] Soil erosion is the main contributing factor. Excessive sediment loads have many undesirable effects on receiving waters, such as siltation and smothering of aquatic ecosystems, turbidity, and reduced light penetration causing changes to primary production. In many instances, sediments may also transport significant loads of nutrients, heavy metals and organochlorines, as these materials are commonly attached to sediment particles.

Acid sulfate soils (ASS) are found in low-lying coastal areas and contain high concentrations of sulfide minerals (mainly iron pyrite, FeS_2).[2] ASS are relatively harmless in their undisturbed (submerged) state but may generate large quantities of sulfuric acid when exposed to the atmosphere through excavation, dredging or lowering of the water table. In addition, iron and aluminium metals may become soluble under acid conditions (Al^{3+}, Fe^{2+} and Fe^{3+}) and enter rivers and estuaries where they may have detrimental effects on aquatic organisms. Major fish and crustacean kills, outbreaks of red-spot disease in fish and increased incidence of acid-tolerant mosquitoes have been linked to the disturbance of acid sulfate soils.

Other "common" contaminants are also found in coastal environments.[2,3,7] Organochlorines from agricultural and industrial applications, including

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Box 1: Estuarine water quality as a coastal stress indicator

Estuarine eutrophication is a key barometer of coastal environmental stress and is consistently ranked as one of the leading problems in coastal management in developed countries.

Eutrophication is a process in which the addition of nutrients to water bodies, primarily nitrogen and phosphorus, stimulates algal growth. The process occurs naturally but is greatly accelerated by human activities. The large nutrient input unbalances the food web, resulting in high levels of phytoplankton biomass in stratified water bodies and leading to algal blooms.

The first stage of water quality degradation associated with eutrophication is characterised by three primary symptoms: decreased light availability, changes in algae, and increased organic matter production. In many estuaries, these primary symptoms lead to secondary symptoms: loss of submerged aquatic vegetation, increases in nuisance or toxic algal blooms, and low dissolved oxygen.

The ratio of nitrogen to phosphorus compounds in a water body determines which of the two elements will be the limiting factor for aquatic life, and consequently needs to be controlled in order to reduce a bloom. Generally, phosphorus tends to be the limiting factor for phytoplankton in fresh waters. Large marine areas frequently have nitrogen as the limiting nutrient, especially in summer. Intermediate areas such as river plumes are often phosphorus-limited during spring, but may turn to silica or nitrogen limitation in summer. When phosphorus is the limiting factor, a phosphate concentration of 0.01 mg l^{-1} is enough to support plankton and concentrations from 0.03 to 0.1 mg l^{-1} or higher will be likely to promote blooms.

In coastal areas, the growth and proliferation of diatoms is promoted by the presence of silica. When the silica concentration is low, diatoms cannot develop. No longer submitted to competition, other opportunistic toxic algal species then grow rapidly and form blooms. Species from the genus *Phaeocystis* and several dinoflagellates (*Prorocentrum, Dinophysis, Gymnodynium*) are known to proliferate under such conditions, and it is these cyanobacteria that have been linked to health effects in animals and humans.

Parameters relevant to eutrophication monitoring

Parameter	Relevance to monitoring eutrophication	Cost per analysis/ Euros
Nitrogen and phosphorus	Indicators of eutrophication and potential bloom occurrence. Reflect the balance between a large number of physical and biological processes. Information is needed on both inorganic and dissolved organic forms of N and P.	60
Silicon	Indicator of freshwater dispersion and of potential for diatom blooms. Si deficiency in coastal waters can favour dinoflagellate blooms.	10
Suspended solids	Relevant indicator for drinking water production.	15
Dissolved oxygen	Essential information with regard to eutrophication effects. It is the key indicator to detect the beginning of a eutrophication process.	5
Bacteria	Microbial processes happen within the cycle of aquatic life and are relevant in the assessment of eutrophication and nutrient budgets.	10
Algal or cyanobacterial biomass	Increased algal or cyanobacterial biomass is a characteristic of eutrophication. Information is also useful for assessing the effects of eutrophication on the ecosystem. Biomass can be determined directly by microscopic counts or indirectly by measurement of pigments such as chlorophyll-a. Other measures are available such as the determination of the amount of suspended particulate organic matter or the automated analysis of number and size of particles.	Variable
Development of short living species of macrophytes	Relevant indicator of a potential disturbance of the recreational use of the waters and of an imbalance of the aquatic ecosystem. Cost depends upon the observation mode.	Variable

Source: adapted from refs. 7 and 8.

pesticides, can bioaccumulate within marine organisms to toxic levels. Some are suspected endocrine disrupters. Heavy metals may enter the marine and estuarine ecosystems from discharges of industrial waste, treated sewage, stormwater run-off, mining operations and other diffuse sources. Again they tend to accumulate in soils, sediments and living organisms and may become concentrated in organisms higher up the food chain. Pathogens such as faecal coliforms and enterococci enter the marine environment through the discharge of sewage *via* ocean outfalls and from stormwater system overflows to rivers and streams. These pathogens pose threats to human health through gastroenteritis, hepatitis and other diseases.

Other stressors may also contribute to or exacerbate pollution impacts.[3,7] Extreme weather events, such as strong storms, can degrade habitats by altering freshwater flow and nutrient concentrations. They can also influence harmful algal blooms (HABs) and lead to increased pollution. Ballast water from ships can be a major source of both oil pollution and invasive marine species which can upset indigenous ecosystems. And, of course, coastal zones are at the sharp end of climate change. Altered sea level conditions, water temperatures, currents, and stratification can lead to other changes in salinity, tides and erosion—forces that shape the marine ecosystem in ways that we have yet to fully understand.

Approaches to coastal pollution control

Historically, coastal and marine pollution control has been approached from a sectoral perspective, through a complex mix of rather narrowly-targeted, and in some cases contradictory, regulatory measures. Thus, coastal management is affected by legislation relating to industrial pollution control, municipal wastewater management, bathing water quality, hazardous waste and sea dumping, discharges from shipping, and habitat and species conservation.

The European Union typifies this approach, with marine protection being based on a mish-mash of directives with no overarching strategy for the marine environment. Key measures include: the EU's 1991 directive on water pollution caused by nitrates from agricultural sources; the 1976 directive on bathing water quality (currently under revision); and the 1992 habitats directive, which aims to promote biodiversity through robust conservation measures.

Perhaps the EU's most comprehensive measure so far is the

Water Framework Directive (WFD) of 2000, which establishes a framework for the protection of all inland surface waters (rivers and lakes), transitional waters (estuaries), coastal waters and groundwater.[9] In relation to the marine environment, the Directive introduced specific measures to cease or phase out discharges, emissions and losses of priority hazardous substances, with the ultimate aim of achieving concentrations near background values for naturally occurring substances and close to zero for man-made synthetic substances. The WFD requires water quality, including estuaries and coastal waters, to be classified into five categories: high, good, moderate, poor, and bad.

Recognising the weaknesses in the current piecemeal approach, the European Commission has recently proposed a new marine strategy based on principles of ecosystem management.[10] The Marine Strategy would comprise a "package" of a communication (policy paper) and a framework directive. Although both have yet to be formally published, the recent consultation exercise provides a clear steer on their likely orientations.

Marine protection should, the Commission says, recognise the difference in the character of the EU's marine areas. These differences are apparent in terms of their physical, chemical and hydrological characteristics, their ecology, the pressures and threats impacting upon the seas and the economic and social conditions of the bordering countries. This points clearly towards an ecosystem-based approach, says the Commission, in line with the concept of sustainable development. Such an approach emphasizes *"a management regime that maintains the health of the ecosystem alongside appropriate human use of the environment, for the benefit of current and future generations"*.

The Commission recommends ecosystem-based marine regions as being the most appropriate level to prepare implementation plans. These regions will be defined under the new marine framework directive based on their hydrological, oceanographic and bio-geographic features. The aim should be to apply the ecosystem-based approach by 2010, with specific measures foreseen for hazardous substances, nutrients, ionizing radiation and discharges from ships. A strong emphasis is placed on monitoring and assessment programmes to evaluate the success of these implementation plans in practice.

In the United States, too, legislation is still fragmented. Key measures include the Clean Water Act, and in particular the Beaches Environmental Assessment and Coastal Health (BEACH) Act of 2000,[11] and the Coastal Zone Management Act of 1972, with the Coastal Zone Act Reauthorization Amendments (CZARA) of 1990.[12] CZARA tackles, among other issues, the non-point source (NPS) pollution problem in coastal waters. Section 6217 of the Act requires coastal states and territories to develop Coastal Non-point Pollution Control Programs describing how they will implement NPS pollution controls. First phase programs were due to be implemented by 2004 and second phases, where necessary, by 2009.

Coastal monitoring programmes

Monitoring plays a crucial role in the assessment and management of coastal and marine environments.

Standard chemical and biological analyses are routinely used. For instance, the National Status and Trends Program (NS&T) in the US has been collecting data on the environmental quality of coastal and estuarine waters since 1984 by monitoring chemical and biological contaminants in sediments, benthic fish and bivalve tissues (see Box 2).[13] The long term nature of the datasets allows scientists to track changes in coastal environmental quality over time. Using sophisticated geographic information systems, they have applied the results of the NS&T contaminant studies to determine relationships between land use and contaminant levels in US estuaries.

In the EU, the regime for coastal and inshore monitoring is set by the Water Framework Directive.[14] This is based mostly on chemical parameters, although monitoring of biological parameters is increasing, largely as a result of international frameworks such as OSPAR (for the North Sea), HELCOM (for the Baltic Sea) and MEDPOL (the Mediterranean).

Ecological monitoring is also a frequent requirement of coastal surveys, including under statutory monitoring programmes such as those required by the EU Habitats Directive and the Water Framework Directive. Such surveys must be quality assured to give a high level of confidence in the results, particularly where complex and expensive management actions may result.

Many marine monitoring techniques require the taxonomic identification of the species present and therefore there is an increasing demand for quality control standards for both epibiota (surface dwelling) and infaunal (sediment dwelling) species.[15] Furthermore, many techniques use imaging systems (photographs or video) and species must be identified from images. In the UK, for instance, conservation agencies have setup the National Marine Biological Analytical Quality Control (NMBAQC) Scheme to monitor marine biological data quality. Among other initiatives, the Scheme is pioneering epibiota recording based on photographic identification.

As well as monitoring for environmental quality and conservation, extensive data are collected within the coastal and marine environment for other purposes.[16] Over recent years the science of oceanography

Box 2: Mussels as environmental indicators

Since 1986, the US Mussel Watch Project, part of the National Status and Trends (NS&T) Program, has monitored chemical contaminants in oysters and mussels and in sediments. Mussel Watch sites are selected to be representative of large coastal areas and to avoid small-scale patches of contamination, or "hot spots." For this reason, its data can be used to compare contaminant concentrations across space and time to determine which coastal regions are at greatest risk in terms of environmental quality.

Presently, over 280 US coastal and estuarine sites are sampled for bivalves biennially and for sediments once every decade. Bivalve and sediment samples are collected from three stations at each site (stations are generally within 100 m of a site center). Tissue contaminant concentrations are measured in several bivalve species.

The Mussel Watch Project determines concentrations of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCB) congeners, several pesticides, butyltins, and certain toxic elements in sediment and bivalve samples from US coastal waters. The data are used to determine the extent and temporal trends of chemical contamination on a nationwide basis and identify which coastal areas are at greater risk in terms of environmental quality.

Adapted from ref. 13.

has emerged as a key contributor to our understanding of climate change and efforts are being intensified in all forms of oceanographic measurements. And from a different perspective entirely, routine monitoring of fish stocks provides an essential basis for fisheries policy. At present these various purposes are largely addressed through discrete and unconnected monitoring efforts.

Towards an integrated approach

Clearly, the marine environment, and the coastal zone in particular, is highly complex. The traditional compartmentalised approach, where we focus on the impacts of individual activities—industrial pollution, sewage discharges, tourism, severe weather events *etc.*—in isolation from all the others gives us only part of the picture. If we are to manage the marine environment in a way that is truly sustainable then we need to better understand how all the various natural and anthropogenic pressures interact. Only then will we be able to move towards a more integrated approach to protecting the marine and coastal environment.

This, in turn, calls for more integrated approaches to marine monitoring.[16,17] We have to find ways to inter-relate and interpret the various kinds of marine data—ocean processes, habitats and species, environmental quality, and marine fisheries—in terms that support policy actions.

The changes necessary in moving towards this integrated approach are wide-ranging and go well beyond the scientific community.[18] They include:

1. *Marine indicators and marine monitoring*: an integrated assessment of the marine environment calls for new types of ecosystem indicators. This is a huge challenge given the range of aspects to be covered in the marine environment and the lack of scientific understanding of some of the interactions. Similarly, we need a more pragmatic risk-based approach to monitoring, in place of current programmes which tend to be sector-based and driven by environmental compliance.

2. *Better links to policy*: the ecosystem approach demands a very wide range of information and expertise. Special efforts will be needed to capture this knowledge so that it can be more effectively integrated into policy-making. As in other areas involving evidence-based policy, this calls for “joined up working” between government and international agencies, research funders and the wider (marine) science community.[19] Researchers must build more transparent routes for transferring their expertise and knowledge to policy and decision-makers.

3. *Information access and stewardship*: much of the existing marine environmental data could be used more effectively if it were available more easily. Government agencies, research institutes and the private sector should co-operate more closely in collecting, managing and disseminating information, including in the development of standard protocols and procedures.

4. *Marine research*: moves towards the ecosystem approach have highlighted that we still have rather a limited understanding of the marine ecosystem and its various components. There are many gaps in the scientific evidence (for an initial list see ref. 16). Ones where environmental monitoring and the analytical sciences can make important contributions include:

- The effects of endocrine disrupters and of contaminant mixtures on marine species and whether such mixtures affect the long-term viability of populations;
- Natural variability of ecosystems and distinguishing this from anthropogenic pressures;
- Ecosystem models for sustainable exploitation of marine resources;
- Longer term changes to ecosystems associated with pressures such as climate change and means to adapt to such changes.

5. *Marine climate change impacts*: climate change could have major effects on the marine ecosystems, factors which at present are little understood. It is therefore essential to develop a better understanding of how climate change affects the marine environment and ensure that this is integrated with the broader work and research.

Our seas and coasts, and the societies they serve, are under pressure like never before. An integrated approach to monitoring, assessment and management will ensure we are able to sustain these assets for future generations.

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