Marine Pollution
in the United States

Prepared for the Pew Oceans Commission by

Donald F. Boesch
University of Maryland Center for Environmental Science

Richard H. Burroughs
University of Rhode Island

Joel E. Baker
University of Maryland Center for Environmental Science

Robert P. Mason
University of Maryland Center for Environmental Science

Christopher L. Rowe
University of Maryland Center for Environmental Science

Ronald L. Siefert
University of Maryland Center for Environmental Science

Contents

Abstract

Direct discharges of pollutants into the ocean and coastal waters from sewage treatment plants, industrial facilities, ships, and the at-sea dumping of sewage sludge and other wastes have been greatly reduced over the past 30 years as a result of the Clean Water Act and other federal statutes. Advances in waste treatment have kept ahead of increases in the volume of wastes, and that trend is likely to continue. Some persistent toxic pollutants, such as DDT and PCBs, were banned for manufacture or use in the United States, and ambient levels of these pollutants have been decreasing in most U.S. marine environments. On the other hand, pollution from land runoff went largely unabated during this period; in some cases it has increased. As a result, diffuse sources now contribute a larger portion of many kinds of pollutants than the more thoroughly regulated direct discharges.

Toxic pollutants, including pesticides, industrial organic chemicals and trace metals, are widespread contaminants of the marine environment. But they produce discernible adverse effects on ecosystems only in limited areas around population centers and ports. Some of these chemicals are known through experimental studies to affect the reproductive, immune, or endocrine systems of marine organisms at low concentrations, and may have subtle effects on marine organisms and populations over a broader area. While some of the most toxic substances have been banned for manufacture and use, material previously released may remain in the environment for decades to centuries. High

Nutrient Overenrichment

The dominant form of plant life in the world's oceans is free-floating, single-celled algae known as phytoplankton. Like all plants, phytoplankton need nutrients—nitrogen, phosphorus, and other minerals—and light to grow and reproduce. Most of the needed nutrients either wash into the ocean from the land or move from the deeper waters to the surface through upwelling.

The growth of phytoplankton is usually limited by the availability of nutrients. Nitrogen is the nutrient that is usually in the shortest supply. But if nitrogen becomes abundant, the growth of phytoplankton can increase dramatically. An explosive increase in the population of phytoplankton is known as an algal bloom. A bloom often contains more phytoplankton than can be eaten by marine animals. The uneaten algae—and wastes from animals that eat the algae—sink to the ocean bottom, and decompose.

Through the process of decomposition, the dissolved oxygen levels in the water near the bottom can decrease substantially.

The long-term increase in the supply of organic matter to an ecosystem—often as a result of excess nutrients, or nutrient overenrichment—is called eutrophication.

concentrations of persistent contaminants in bottom sediments require careful consideration when removed by dredging or managed in place.

Overenrichment of coastal ecosystems by nutrients, particularly nitrogen, has emerged as the most widespread and measurable effect of pollution on living marine resources and biodiversity in U.S. coastal waters. Excessive nutrient levels (overenrichment or eutrophication; see sidebar on these pages) may result in serious depletion of the dissolved oxygen supplies needed by marine animals, loss of habitat (e.g., seagrasses and coral reefs), and algal blooms. Two-thirds of the surface area of estuaries and bays in the conterminous U.S. suffers one or more symptoms of overenrichment. Because a majority of the nutrients in most regions now come from diffuse sources rather than direct discharges, reversing coastal eutrophication will require management strategies for watersheds reaching far inland from the coastal environment. Feasible measures include advanced treatment of municipal wastewaters, reduction of nitrogen oxide emissions from power plants and vehicles, control of ammonia emissions from animal feedlots, more efficient use of fertilizers and manure, and restoration of wetlands and floodplains that act as nutrient traps.

Eutrophication creates two harmful effects: oxygen depletion and reduced water clarity. When dissolved oxygen levels drop to levels that equal two milligrams per liter or less, a condition called hypoxia occurs.

Anoxia refers to a complete absence of dissolved oxygen in the water.

More mobile marine animals, like fish and crabs, can often migrate out of hypoxic areas. Other animals—such as oysters and marine snails—that lack mobility or cannot move quickly enough to escape hypoxia may suffocate. When water clarity is reduced by greater concentrations of algae, less light can penetrate to the ocean bottom where seagrasses and seaweeds live. As a result, these plants may sicken and die.

Increased nutrient levels in surface water (rivers and streams) and in groundwater from the land can be attributed to human activity. Major sources of nitrogen, phosphorus, and other nutrients delivered to the oceans include discharges from wastewater-treatment plants, runoff and groundwater from cropland, urban and suburban stormwater (runoff from paved surfaces), farm animal wastes, and even nutrients found in airborne emissions from power plants, automobile exhaust, and industrial smokestacks.

I. Introduction

This report provides background on the effects of pollution on life in the ocean and coastal waters of the United States for the Pew Oceans Commission, which is conducting a national dialogue on policies needed to restore and protect living marine resources. Pollution occurs when a substance, an organism, or energy (e.g., sound or heat) is released into the environment by human activities and produces an adverse effect on organisms or the environmental processes on which they depend.

"Pollution occurs when a substance, an organism, or energy (e.g., sound or heat) is released into the environment by human activities and produces an adverse effect on organisms or the environmental processes on which they depend."

Marine pollution comes in many forms and from many sources (Table 1). Some pollutants in sufficient concentrations are toxic to marine organisms. These include both naturally occurring chemicals present in much higher concentrations as a result of human activities (e.g., trace metals and oil) as well as compounds that did not exist in nature until manufactured by humans (e.g., pesticides such as DDT).

Other pollutants are harmful not because they are toxic but because they stimulate biological activity or alter habitats. The addition of large amounts of organic matter in the form of sewage or fish-processing wastes, for example, supports the growth of decomposer microbes that can exhaust the available oxygen supply. Inputs of nutrients (particularly forms of nitrogen and phosphorus), while responsible for the rich biological productivity of many coastal waters, can stimulate the production of more organic matter than an ecosystem can assimilate. Turbid waters, depletion of oxygen, and blooms of noxious algae may result. Sediments from land runoff or from dredging can decrease water clarity and smother sensitive bottom habitats such as reefs and seagrass beds.

Pollution emanates from either direct discharges or diffuse sources. Land-based industrial and municipal outfalls discharge wastewater into coastal waters or rivers that drain to the coast. Other direct discharges include those from vessel operations and at-sea waste disposal. Pollutants from diffuse sources include those released into the atmosphere by fossil-fuel and waste combustion; and land runoff of pesticides, toxic-waste products, nutrients, and sediments. Although chemical contaminants—released as a result of human activities—can now be found throughout the world's oceans, most demonstrable effects on living resources occur in coastal waters and are the result of pollution from land.

Table 1

Forms of Marine Pollution

Form	Sources	Effects and Trends
Toxins (e.g., biocides, PCBs, trace metals)	Industrial and municipal wastewaters; runoff from farms, forests, urban areas and landfills; erosion of contaminated soils and sediments; vessels; atmospheric deposition	Poison and cause disease and reproductive failure; fat-soluble toxins may biocencentrate, particularly in birds and mammals, and pose human health risks. Inputs into U.S. waters have declined, but remaining inputs and contaminated sediments in urban and industrial areas pose threats to living resources.
Biostimulants (organic wastes, plant nutrients)	Sewage and industrial wastes; runoff from farms and urban areas; airborne nitrogen from combustion of fossil fuels	Organic wastes overload bottom habitats and deplete oxygen; nutrient inputs stimulate algal blooms (some harmful), which reduce water clarity, cause loss of seagrasses and coral reefs, and alter food chains supporting fisheries. While organic waste loadings have decreased, nutrient loadings have increased (NRC, 1993a, 2000a).
Oil	Runoff and atmospheric deposition from land activities; shipping and tanker operations; accidental spills; coastal and offshore oil and gas production activities; natural seepage	Petroleum hydrocarbons can affect bottom organisms and larvae; spills affect birds, mammals and nearshore marine life. While oil pollution from ships, accidental spills, and production activities has decreased, diffuse inputs from land-based activities have not (NRC, 1985).
Radioactive isotopes	Atmospheric fallout, industrial and military activities	Few known effects on marine life; bioaccumulation may pose human health risks where contamination is heavy.
Sediments	Erosion from farming, forestry, mining, and development; river diversions; coastal dredging and mining	Reduce water clarity and change bottom habitats; carry toxins and nutrients. Sediment delivery by many rivers has decreased, but sedimentation poses problems in some areas; erosion from coastal development and sea-level rise is a future concern.
Plastics and other debris	Ships, fishing nets, containers	Entangles marine life or is ingested; degrades beaches, wetlands and nearshore habitats
Thermal	Cooling water from power plants and industry	Kills some temperature-sensitive species; displaces others. Generally, less a risk to marine life than thought 20 years ago.
Noise	Vessel propulsion, sonar, seismic prospecting, low-frequency sound used in defense and research	May disturb marine mammals and other organisms that use sound for communication.
Human pathogens	Sewage, urban runoff, livestock, wildlife	Pose health risks to swimmers and consumers of seafood. Sanitation has improved, but standards have been raised (NRC, 1999a).
Alien species	Ships and ballast water, fishery stocking, aquarists	Displace native species, introduce new diseases; growing worldwide problem (NRC, 1996).

Adapted from Weber, 1993.

The report first reviews accomplishments in reducing marine pollution, and then highlights the need for further reductions in the effects of toxic substances and nutrients as remaining major challenges. Diffuse sources of pollution via land runoff and atmospheric deposition are particularly important and have proved difficult to control. To provide grounding for policies needed to restore and protect living marine resources, the report: describes the forms, sources, movements, and effects of pollutants; assesses past and future trends of pollution in the U.S.; considers additional steps that could reduce pollution; and places pollution threats into a broader context of other threats to living resources.

II. Reductions of **Pollution**

Municipal and Industrial Discharges

In 1972, Congress passed the landmark Federal Water Pollution Control Act, which was reauthorized in 1977, 1981, and 1987 as the Clean Water Act (CWA). The goal of the law is to eliminate pollution in the nation's waters. It imposes uniform minimum federal standards for municipal and industrial wastewater treatment based on best available technology. Facilities discharging wastes at discernible points are required to obtain permits from the U.S. Environmental Protection Agency (EPA) or from state pollution-control agencies. Permits include enforceable limits on pollutants in the discharges, and require dischargers to conduct monitoring and to file reports when limits are violated.

Most publicly owned treatment works (POTWs) handle industrial wastes as well as domestic sewage. Because discharges of untreated organic wastes had degraded many rivers, lakes, and coastal waters by depleting dissolved oxygen and causing fish kills, the Clean Water Act required POTWs to achieve at least "secondary" treatment. Secondary treatment adds biodegradation of the organic matter in the wastewater to the solids (sludge) removal and disinfection included in "primary" treatment. Consequently, it significantly reduces the biological oxygen demand (BOD) of wastewater effluent. The CWA provided substantial amounts of money to help pay for the required POTW improvements. About 125 billion dollars have been spent in constructing or expanding POTWs, mainly between 1972 and 1992 when federal grants provided three-quarters of the costs (NRC, 1993a). Waivers to this requirement were allowed for several deep ocean outfalls where it could be demonstrated that the organic wastes would not harm the environment. Additional waste treatment, such as reduction of suspended solids, was often required.

Technology-based standards and the National Pollutant Discharge Elimination System (NPDES) have resulted in a dramatic reduction in the amount of pollutants entering U.S. waters, including coastal waters. Reductions in discharges of organic matter improved conditions in the Delaware River estuary near Philadelphia to the point that low oxygen levels no longer prevent the upriver migration of juvenile striped bass and American shad (Weisberg et al., 1996). Oxygen levels in New York Harbor are approximately 50 percent higher (NRC, 1993a). The most thoroughly documented example of the benefits of improved treatment may be the Southern California Bight, off Los Angeles and San Diego (Box 1), where inputs of many pollutants have been reduced 90 percent or more over a 25-year period. Kelp beds, fish and invertebrate communities, and certain seabird populations have greatly, if not completely, recovered. These improvements have been accomplished despite a steady increase in population and in the volume of wastewater discharged.

Another long-term effort to restore water quality has recently come to fruition with the completion in September 2000 of a new deepwater outfall for treated effluents from the Boston region. The offshore discharge into Massachusetts Bay will result in improvements in environmental quality in Boston Harbor beyond those already achieved as a result of the cessation of sludge disposal, reductions in combined sewer overflow, and secondary treatment of

Box 1

Southern California Bight Ocean Discharges

Wastes from the nation's largest metropolitan center (17 million people) are discharged into a bight of the Pacific Ocean via deepwater (about 200 feet) outfalls. Pollution from publicly owned treatment works (POTWs) has been reduced significantly since the 1970s even though the population served and wastewater volumes grew steadily (Schiff et al., 2000; Figure 1). This reduction was accomplished through source control, pretreatment of industrial wastes, reclamation, and treatment-plant upgrades, including secondary or other advanced treatment (concentrating on chemical removal of suspended solids). Capital improvements to POTWs throughout the Southern California Bight cost more than five billion dollars.

Discharges from POTWs of most pollutants into the bight have decreased: 50 percent for suspended solids and biological oxygen demand, 90 percent for combined trace metals, and more than 99 percent for chlorinated hydrocarbons. Bight sediments show a record of decreasing contamination. Concentrations of contaminants in fish and marine mammals have declined. Kelp beds near the POTWs have returned. The extent of degraded bottom communities has contracted by about two-thirds; and the incidence of tumors and other maladies in bottom fish has returned to background levels.

A unique problem for the bight is the fact that large quantities of the pesticide DDT were previously discharged, particularly through the Los Angeles County's POTW. This facility received wastes from the world's largest DDT manufacturer. In 1971 an estimated 440,000 pounds of DDT were discharged via an outfall off Palos Verdes. Today, only 3 pounds of DDT are discharged from all Southern California POTWs combined (Schiff et al., 2000). Concentrations of DDT and its degradation products have declined greatly in fish and marine mammals. Populations of brown pelicans, which were decimated by the eggshell thinning induced by DDT contamination, have rebounded. However, brown pelicans, bald eagles, and peregrine falcons are still being affected by the residual DDT contamination in the bottom sediments of the bight. Although this "legacy" contamination is slowly being buried, some DDT is still remobilized into the food chain.

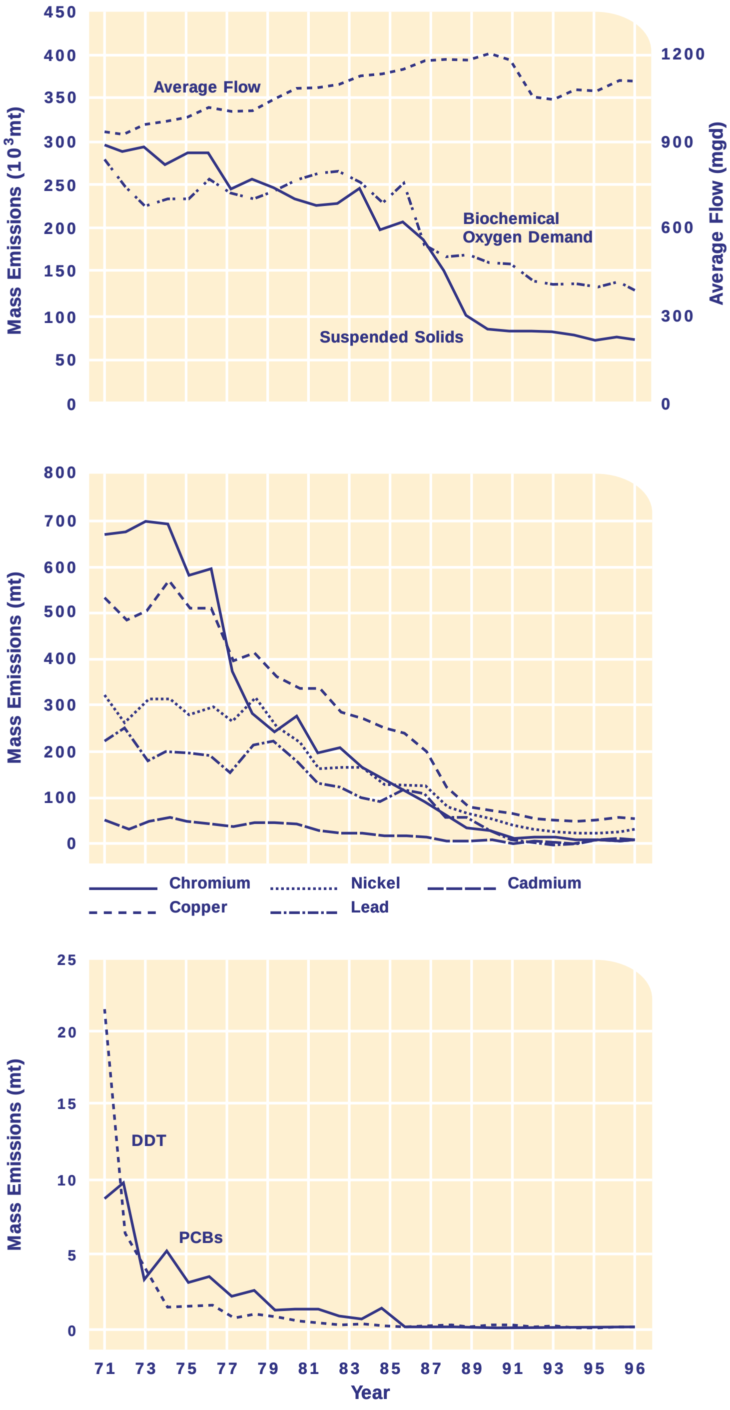
wastes. Although recovery is far from complete, liver tumors in flounder are less common, mussels accumulate lower levels of organic contaminants, and bottom invertebrate communities are recovering in the harbor (Rex, 2000). Field studies and computer models predict that moving the discharge offshore to deeper waters will not increase concentrations of pollutants, including nutrients, in Massachusetts Bay.

Although secondary treatment of municipal sewage removes at least 85 percent of the organic material and suspended solids in wastewater, only one-third of the nitrogen and phosphorus is eliminated (NRC, 1993a; NRC, 2000a). These two nutrients are the principal causes of eutrophication of receiving waters (see Section IV). Advanced treatment technologies, capable of eliminating up to 97 percent of the nitrogen and 99 percent of the phosphorus (NRC, 2000a), are being implemented in regions susceptible to nutrient overenrichment from direct discharges.

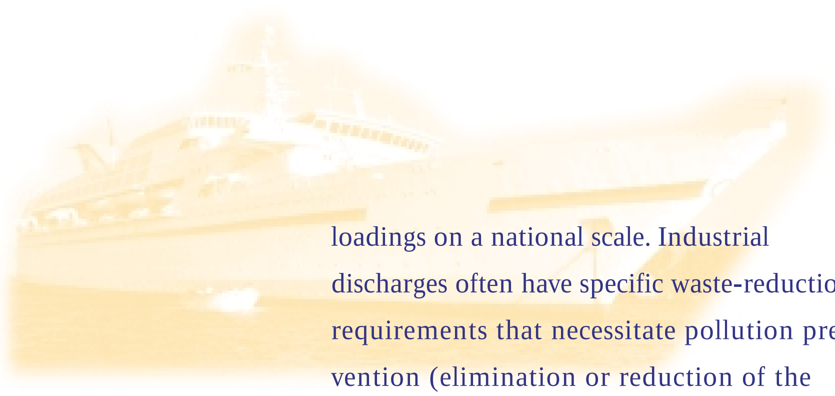
Pollutant levels have also been reduced in discharges from industries, including oil and gas production, refineries, chemical manufacturing, electric-power generation, and food processing. Although regionally important, industrial discharges contribute a relatively small portion of pollutant

Figure 1

Flow Volume and Pollutant Emissions from Four Largest Publicly Owned Treatment Works in the Southern California Bight, 1971 through 1996.



Source: Raco-Rands, 1999; Schiff et al., 2000.



loadings on a national scale. Industrial discharges often have specific waste-reduction requirements that necessitate pollution prevention (elimination or reduction of the source in the industrial process), recycling and reuse, and advanced waste treatment.

Pollution from aquaculture—effluents from ponds or holding tanks on land and materials released from net pens and shellfish racks or rafts—is receiving new regulatory attention with the expansion of aquaculture in coastal waters. Pollutants include uneaten food, fecal and excretory material, and releases of antibiotics, pesticides, hormones, anesthetics, pigments, vitamins, and minerals. Organic deposits under net pens and shellfish rafts often alter the bottom habitat and affect seabed communities in the immediate vicinity. Extensive aquaculture operations can constitute a major source of nutrient inputs to the smaller bays and estuaries in which they are located. Antibiotic, pesticide, and hormone releases can also affect wild organisms in the region (Goldburg and Triplett, 1997).

Additional reductions of pollution from direct discharges will undoubtedly be required and more effective source controls and treatment technologies developed to meet those requirements. Two forces are driving these reductions. First, the Clean Water Act requires dischargers to implement advanced pollution controls where conventional technology is not sufficient to protect aquatic life and the human uses assigned to the water body receiving the discharge. Standards for designated uses are not currently met for one-third of U.S. waters (EPA 2000a). In such cases, the Clean Water Act specifies that total maximum daily loads (TMDLs) be determined and allocated among point and nonpoint sources. Second, ever-closer scrutiny is given to the inputs of chemicals that induce toxicity at very low concentrations, persist in the environment for long periods, and reach high levels of accumulation in the tissues of fish and wildlife.

Vessel Discharges

Pollutants are discharged to the ocean from the routine operations of ships and boats (including discharges of sewage and industrial-processing wastes and the release of petroleum hydrocarbons from engine exhausts and bilge and ballast waters). Vessel-related pollution may also occur as a result of accidental spills and solid-waste disposals.

At-sea release of oily water has been an international issue over the past 30 years and is regulated under the International Convention for the Prevention of Pollution from Ships. Compartments of oil tankers are typically filled with seawater for ballast when emptied of their cargo. Some ports, such as Port Valdez, Alaska, have ballast-water treatment facilities. Although ballast-water discharges may cause problems along some tanker routes and are responsible for tar balls that contaminate the surface of high seas, they comprise a relatively small percentage of oil pollution in the marine environment (NRC, 1985). Exhaust emissions into the water from smaller vessels may be a significant source of petroleum hydrocarbons in more confined coastal waters.

Atmospheric emissions from ships are being recognized as a significant source of global air pollution (Corbett and Fischbeck, 1997), yet they are not subject to the same restrictions for protection of air quality as are land-based power plants and manufacturers. Seagoing vessels are responsible for an estimated 14 percent of emissions of nitrogen from fossil fuels and 16 percent of the emissions of sulfur from petroleum uses into the atmosphere (Corbett and Fischbeck, 1997).

Cruise ships, although not a major source of pollution to U.S. coastal waters as a whole, can cause problems in areas such as Caribbean island harbors, which accommodate intense cruise-ship activity, or relatively pristine areas such as the inland passages of Alaska. Cruise ships generate sewage, gray water, solid wastes, oily wastes, and waste from photo processors, swimming pools and dry cleaners. (EPA, 2000b).

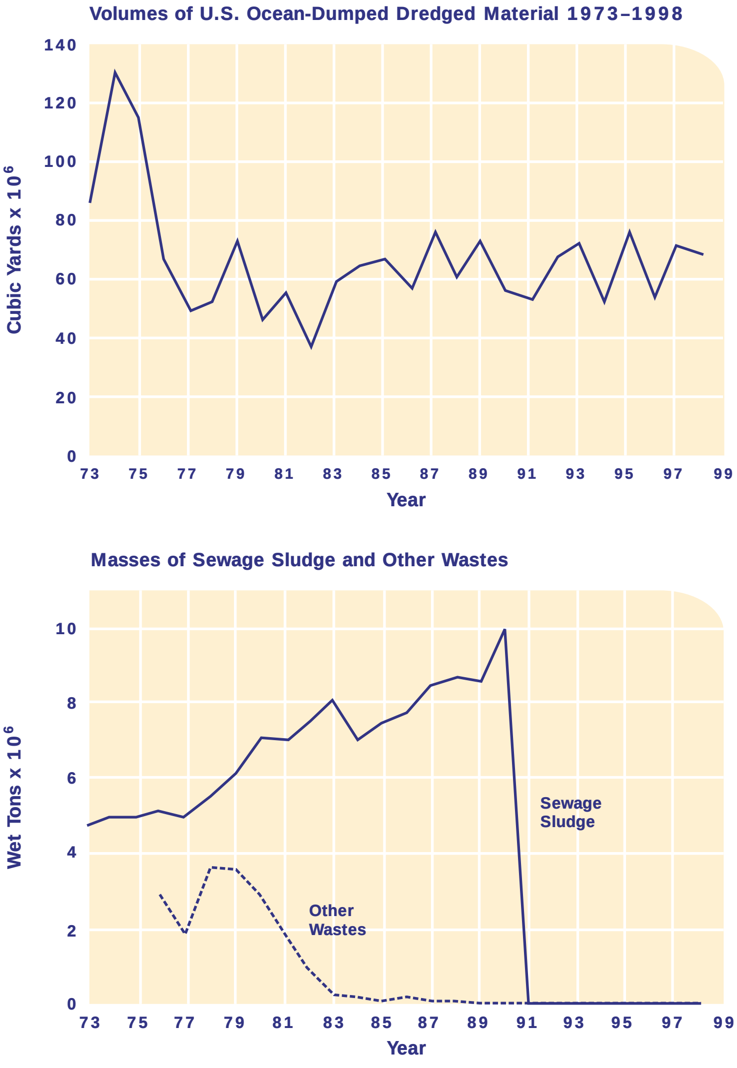
Ocean Dumping

The practice of transporting wastes for disposal in the ocean became a cause for national and international concern in the 1970s (CEQ, 1970). The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters, or the London Dumping Convention, came into force in 1975, acknowledging through its regulatory framework that different materials have vastly different impacts on the marine environment. Nationally, ocean disposal in U.S. waters has been regulated under the Marine Protection, Research, and Sanctuaries Act of 1972 (MPRSA) by a permit procedure that prohibits dumping of some materials, establishes criteria to authorize dumping of others, and identifies sites for disposal. The Clean Water Act also regulates discharges into the territorial sea and navigable waters of the United States. In the ten years following passage of the MPRSA, dumping of industrial waste, construction debris, solid waste, and incineration of chemicals remained low, but dumping of sewage sludge doubled (Burroughs, 1988). Although the amount of dredged sediment disposed in coastal waters remained constant, it was approximately an order of magnitude greater in volume than the sludge dumped (Figure 2).

During the 1980s, public apprehension about ocean dumping grew. Sewage sludge dumped in the New York Bight was blamed for an apparent decline in water quality and health risks to bathers. Controversy also erupted over ocean incineration of chemical wastes in the Gulf of Mexico. In 1988,

Figure 2

Amounts of Dredged Material and Other Wastes Dumped in U.S. Waters, 1973 through 1998



Volumes of U.S. Ocean-Dumped Dredged Material 1973–1998

Masses of Sewage Sludge and Other Wastes

Source: U.S. Army Corps of Engineers, 1999; EPA, 1991.

Congress enacted the Ocean Dumping Ban Act that prohibited ocean dumping of sewage sludge and industrial chemicals. Sewage sludge must now be incinerated, disposed of on land, or reused—alternatives that have their own set of environmental impacts, including pollution of the marine environment via land runoff and atmospheric deposition.

Today, virtually all the material dumped into coastal and marine waters is bottom sediment removed by dredging (Figure 2). Under the Clean Water Act, the U.S. Army Corps of Engineers issues permits for disposal of dredged material, subject to guidelines established by EPA. Protocols have been developed to determine whether dredged sediments are suitable for placement in the ocean or coastal environment. These protocols involve an assessment based on the sediment characteristics, contaminant levels, the toxicity of contaminants present, and the potential for the contaminants to accumulate in the tissues of organisms (EPA, 1991). Based on these criteria, dredging may not be permitted at all or the dredged sediments may be deemed unacceptable for overboard disposal. Placement in a landfill, in a confined disposal facility, or in a contained underwater disposal site is then required. Approximately five to ten percent of the sediments dredged require management as contaminated sediments (NRC, 1997).

Although the federal laws governing dredged material disposal have eliminated the practice of discarding heavily contaminated harbor sediments in the marine environment, they have not eliminated controversies. Despite the protections afforded by regulatory requirements and testing protocols, significant controversies surround the overboard disposal of dredged sediments that are deemed acceptably "clean." These controversies are related in part to the physical impacts of dredged sediment placement, including increased turbidity, siltation, burial of bottom organisms, and permanent changes in the quality of bottom habitat. In addition, the public, resource users, and environmental managers are concerned that contaminants in the dredged sediment will be mobilized and made more bioavailable by overboard disposal. As a result, many ports struggled to resolve impasses in selecting and permitting alternatives for dredged sediment placement (Box 2). On one side, there is an aversion to placing wastes of any kind into the ocean and coastal waters; on the other, there are constraints related to costs, limits in the feasibility of beneficial uses, and opposition to disposal alternatives outside of the marine environment.

The volume of commerce moving through U.S. ports is increasing and will continue to do so because of increased world trade and dependence on foreign

Box 2

San Francisco Bay: Long-Term Strategy for Dredged Material

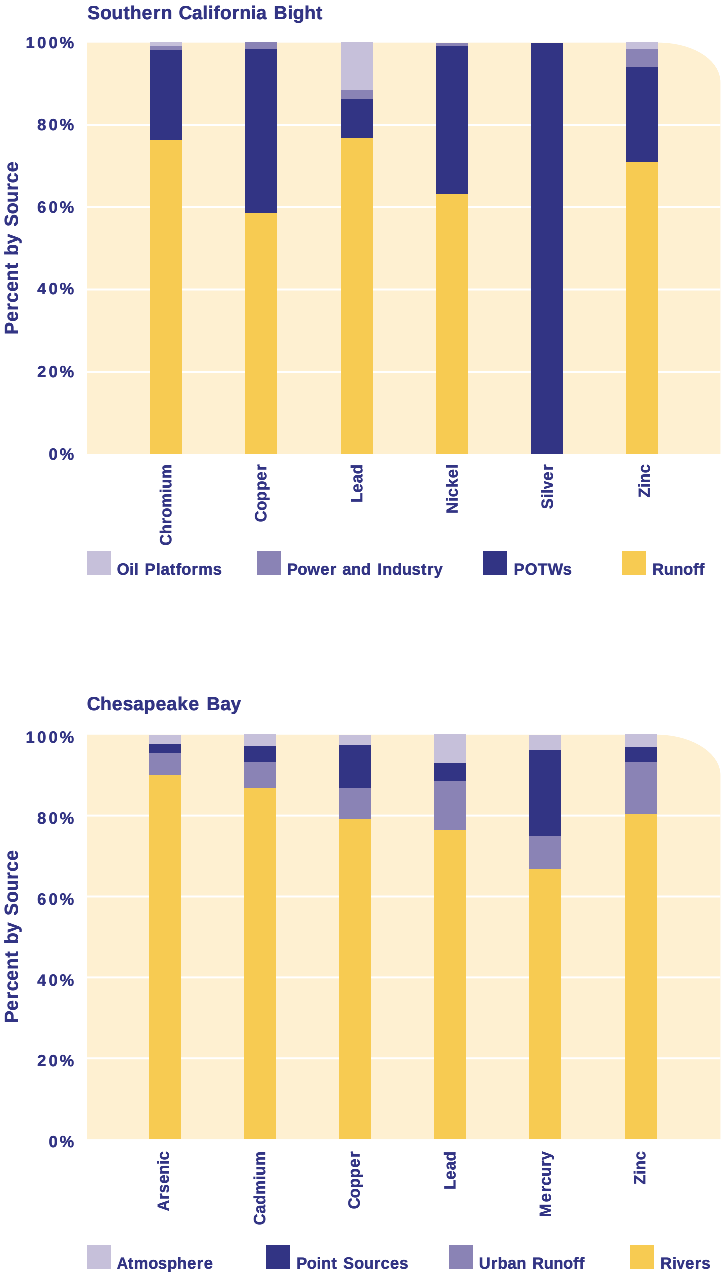
Navigation channels and berths in San Francisco Bay tend to fill in rapidly because of the large amount of mobile sediments in the bay—a legacy of placer mining following the California Gold Rush—and strong tidal currents. Dredged sediments were typically placed back into the bay, mostly at a site near Alcatraz Island, where strong tidal currents dispersed them. However, disposal of large quantities of sediments generated from channel deepening changed the current patterns at the Alcatraz site so that sediments placed there no longer dispersed.

The limitations of this site, the lack of readily available alternatives, public concerns, lawsuits, and fragmented agency management coalesced to create an impasse, or so-called mudlock, that halted most dredging. This caused significant problems for both commercial and military shipping. The U.S. Navy, citing national security requirements, broke the impasse by dumping dredged sediments at a deepwater site in the ocean. Subsequently, EPA designated an ocean disposal site to receive sandy sediments dredged by federally funded projects.

In 1990, federal, state, and regional agencies joined with navigation interest groups, fishing groups, environmental organizations, and the public to develop a Long-Term Management Strategy for Bay Area dredged material (U.S. Army Corps of Engineers, 1998). The strategy emphasizes a balance between ocean disposal and beneficial reuse at upland/wetland sites with limited in-bay disposal. During a transitional period, the amount of dredged material deposited at in-bay sites would be reduced from 80 percent to 20 percent, while upland sites, reuses, and wetland restoration are developed. Toxicity testing and monitoring would be bolstered. Nonetheless, environmental interest groups are calling for the elimination of in-bay disposal altogether.

Figure 3

Sources of Loadings of Trace Metals to the Southern California Bight



Source: Schiff et al., 2000; Chesapeake Bay Program, 1999.

energy resources (Bureau of Transportation Statistics, 2000). This is driving a trend toward larger ships with deeper drafts and, thus, continued pressure for deeper channels. Although there has been an effort to develop a national policy for screening dredged material and evaluating disposal options (Maritime Administration, 1994), the U.S. lacks a coherent port development policy that is compatible with the environmental quality objectives articulated in federal environmental statutes.

Diffuse Sources of Pollution

In most U.S. coastal regions, diffuse sources of pollution—including land runoff and atmospheric deposition—are now responsible for most serious water-quality problems (EPA and USDA, 1998). Because of the reduced loadings of many contaminants achieved by point-source controls, land runoff is currently the dominant source of many contaminants in both the Southern California Bight and Chesapeake Bay (Figure 3).

Except where the manufacture or use of a contaminant has ceased or changed dramatically—such as for DDT and some other pesticides, PCBs, or lead additives in gasoline—the contribution of diffuse sources of pollution in coastal and ocean waters has not been significantly reduced by the programs implemented over the last 30 years. Moreover, loadings of some pollutants from diffuse sources, such as nitrogen (Howarth et al., 1996; Goolsby et al., 2000) and mercury

(Swain et al., 1992), appear to have increased during that time period.

The importance of diffuse sources of pollutants has long been recognized. There are provisions in the Clean Water Act and Coastal Zone Management Act intended to achieve reductions in pollution of coastal waters from diffuse sources. Nonetheless, improvements have been slow and difficult. This is due to the diversity of diffuse sources, resistance to regulatory solutions, and the multiple pathways through which the pollutants may reach coastal and ocean environments.

Fallout from the atmosphere is an important and previously under-appreciated source of a number of important pollutants, including nitrogen, lead, mercury, and organochlorine compounds such as DDT and PCBs (Box 3). Some of these pollutants can be transported over long distances before falling onto the ocean or on watersheds draining to the coast. Atmospheric transport is the primary mechanism for contamination of oceanic regions remote from human activities, such as polar seas and the open ocean. In a recent report to Congress, the EPA (2000c) indicated that atmospheric deposition of PCBs, banned and restricted pesticides, and lead has been declining in recent years for the Great Lakes and some coastal waters, but that deposition of other pollutants such as nitrogen has not fallen off.

Contaminants and nutrients in runoff are influenced by: (1) land uses, i.e., whether the land is forested, agricultural, industrial or urban; (2) human activities that involve the purposeful or unintended placement of fertilizers, pesticides, atmospheric contaminants, and wastes on the land surface; and (3) natural phenomena and land-use decisions that affect water infiltration, retention, groundwater movement, runoff, and transport in streams and rivers.

"Atmospheric transport is the primary mechanism for contamination of oceanic regions remote from human activities, such as polar seas and the open ocean."

Sediments that erode from the land and reach the coast in runoff carry various contaminants bound to sediment particles, including trace metals, organic compounds, and phosphorus. The sediments themselves can constitute a serious form of pollution, silting up shallow water environments, increasing the need for dredging, altering benthic habitats, and decreasing water clarity. Alternatively, improved soil conservation practices and the entrapment of riverine sediments behind dams have resulted in decreased delivery of sediments to many U.S. coastal environments over the last half century (Meade, 1982). For some coastal environments, this has improved the conditions for living resources by increasing water clarity and decreasing sedimentation; however, other coastal ecosystems, such as sandy beaches and subsiding deltas (Milliman, 1997), are experiencing problems because a continued supply of sediments is needed to sustain them. *(Continued on page 14)*

Box 3

The Atmosphere: An Important Pathway for Some Pollutants

Atmospheric deposition of pollutants involves a variety of physical processes that transport chemicals to the Earth's surface (Baker, 1997; Figure 4). Wet deposition involves processes by which gases and airborne particles are washed from the atmosphere during precipitation. Dry deposition results from the impact of fine particles (aerosols) on surfaces and on gas exchange at terrestrial and aquatic surfaces. The magnitude of atmospheric deposition depends directly on the concentration of pollutants in the atmosphere, the form of each chemical (gas or particulate), the size of the aerosol particles, and the extent of precipitation and physical mixing.

Pollutants are introduced into the atmosphere from a variety of sources, travel through several pathways, and reach various fates. Materials such as soot, NO_X, and SO_2, are released from natural sources (forests, volcanoes, and fires) as well as from human activities (anthropogenic sources). However, many atmospheric pollutants (e.g., PCBs, CFCs) are only derived from anthropogenic sources. Sources of air pollutants are commonly categorized as stationary (e.g., power plants, refineries, and incinerators), mobile (vehicles, aircraft, locomotives, and ships), or area (e.g., volatilization of ammonia from manure).

The lifetime of a pollutant in the atmosphere is dependent on its chemical reactivity and its partitioning among gas, liquid, and solid phases. In general, chemicals on particles or in liquid water have a shorter lifetime in the atmosphere and are not transported far from their source, while gaseous chemicals may remain in the atmosphere a long time and travel great distances. Persistent chemicals that are revolatilized after being deposited can travel like a grasshopper over great distances. Because these chemicals are more prone to evaporation under warmer temperatures, they tend to be redistributed to higher latitudes (Wania and Mackay, 1996).

Atmospheric deposition is an important source of nitrogen, some trace metals (e.g., lead and mercury), and organochlorine compounds (e.g., DDT and PCBs) to coastal and ocean environments:

- Lead emissions to the atmosphere in the U.S. and Europe are now orders of magnitude lower than in the early 1970s due to ending the use of leaded additives to gasoline. The impact can be seen in the reduction of lead concentrations in surface waters of the open ocean (Wu and Boyle, 1997), coastal sediments (Bricker, 1993; Cochran et al., 1998; Hornberger et al., 1999), and shellfish tissues (Lauenstein and Daskalakis, 1998).
- The global reservoir of atmospheric mercury has increased by a factor of two to five since the beginning of industrialization (Boening, 2000) and is dominated by anthropogenic emissions (Mason et al., 1994). Principal sources (>80 percent) are combustion processes, primarily coal burning and municipal and medical-waste incineration (EPA, 1997). Higher mercury concentrations in wet deposition are found in urban areas, reflecting local power plant and incinerator sources (Mason et al., 2000). Surface waters of the North Atlantic have higher mercury concentrations compared to the equatorial Pacific (Mason and Fitzgerald, 1996), probably as a result of long-distance transport of gaseous forms of mercury from sources in North America.
- The discovery of organochlorine pesticides such as DDT and industrial chemicals such as PCBs in the waters and biota of the Arctic and Antarctic ecosystems fundamentally altered our view of the role of the atmosphere in distributing pollutants on a global scale (Wania and Mackay, 1996).

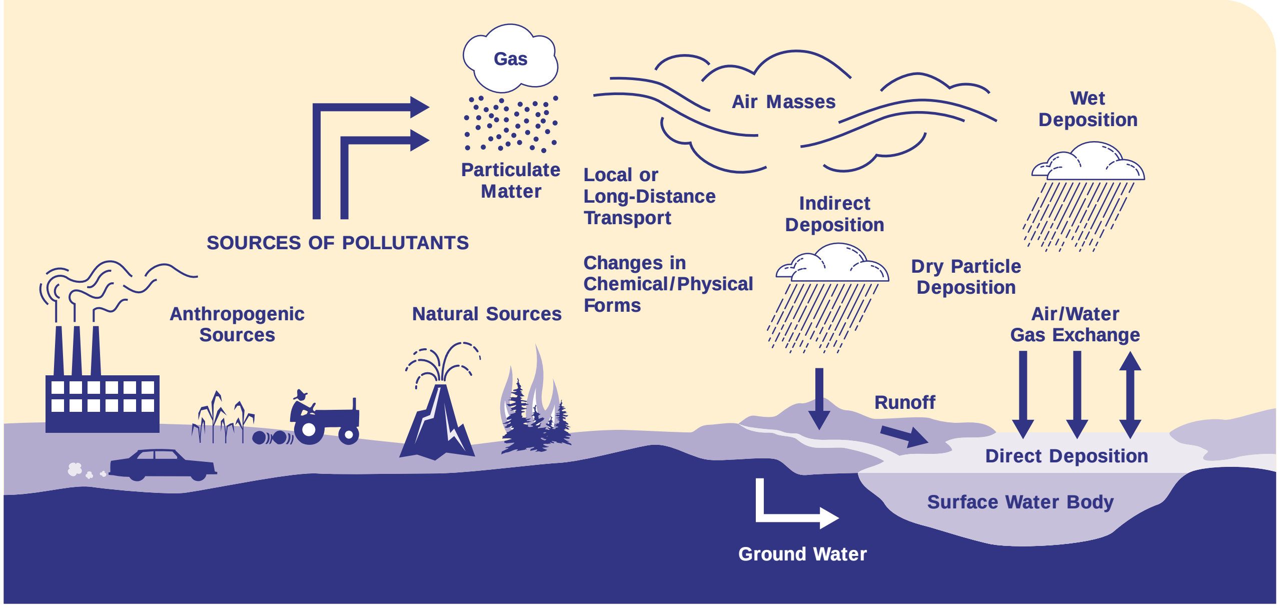
Conversion of lands to urban and suburban uses has been proceeding at a rate far greater than the rate of population growth in many coastal communities as a result of the U.S. tendency for low-density residential development (sprawl). The conversion of previously undisturbed land surfaces that allowed the infiltration and slow release of water to impervious surfaces such as roofs, driveways, roads, and parking lots results in higher peak runoff, which carries greater pollution loads and alters the salinity balance in bays and estuaries during both wet and dry weather periods.

While direct discharges still contribute significant toxic contaminants and nutrients to coastal waters, it is clear that protecting the marine environment from the many adverse effects of pollution will require more effective control of land runoff and atmospheric deposition—now the principal sources of the most damaging pollutants in many coastal ecosystems.

> **"...it is clear that protecting the marine environment from the many adverse effects of pollution will require more effective control of land runoff and atmospheric deposition...."**

Figure 4

Atmospheric Release, Transport, and Deposition Processes



Source: EPA, 2000c.

III.

The Challenge of Toxic Contaminants

Nature of Toxic Contaminants

Toxic pollutants include trace metals (e.g., cadmium, copper, lead, and mercury), a variety of biocides (e.g., DDT, tributyl tin) and their by-products, industrial organic chemicals (e.g., PCBs and tetrachlorobenzene), and by-products of industrial processes and combustion (e.g., polycyclic aromatic hydrocarbons, or PAHs, and dioxins). Those pollutants meriting greatest attention are widespread and persistent in the environment, have a propensity to accumulate in biological tissues, or induce biological effects at extremely low concentrations.

> **"The historic use of some compounds no longer manufactured or used in the United States—like DDT, PCBs, and lead additives in gasoline—has left a legacy of contamination."**

The historic use of some compounds no longer manufactured or used in the United States—like DDT, PCBs, and lead additives in gasoline—has left a legacy of contamination. Generally, legacy contaminants in U.S. coastal environments have declined. However, these compounds are still in use in other countries and they continue to run off the land. For example, it has been estimated that less than 10 percent of the total lead deposited from the atmosphere onto the Sacramento and San Joaquin river basins has yet been delivered to San Francisco Bay (Steding et al., 2000). As the concentrations of some heavy metals and organochlorine compounds decrease in the marine environment, other contaminants are still being released and do not show a clear downward trend. Some may even be increasing. For example, analyses of lake and reservoir sediments show increasing levels of PAHs associated with suburban development (Van Metre et al., 2000). PAHs come from multiple sources, including petroleum and the combustion of fossil fuels and biomass, some of which have been reduced (e.g., coal coking) and some of which continue (e.g., urban runoff and atmospheric deposition of combustion by-products).

Humankind will be dealing with legacy contaminants of the marine environment well into the future. Repositories of persistent contaminants in marine sediments can be sources of long-term exposure to marine life well after the inputs of these contaminants have largely ceased. Examples of this include DDT in the Southern California Bight (Box 1) and PCBs in San Francisco Bay (San Francisco Estuary Institute, 1996). The deep sea may be the final sink for some persistent organic pollutants (Looser et al., 2000).

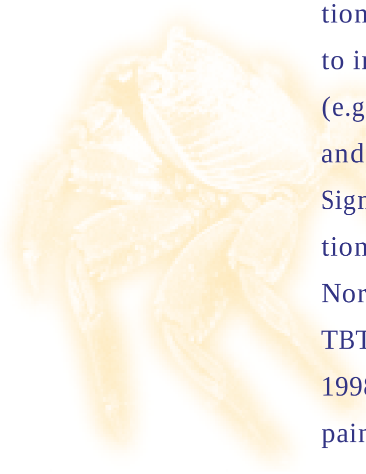
Biological Effects

Toxic effects, both lethal and sublethal, have been extensively documented in laboratory experiments, but concrete examples of contaminant effects on populations of marine organisms are limited (McDowell et al., 1999). Key issues considered here include the potential for bioaccumulation of toxicants by marine life; the effects of disruptions of organisms' immune, endocrine, and reproductive systems on their populations; and the effects on marine communities of chronic exposure to the high concentrations of contaminants found in coastal sediments.

Organisms may accumulate contaminants from water, sediments, or food in their tissues. This can result in concentrations of the contaminant many times higher than those found in the environment. The degree of bioaccumulation depends on the level of exposure and the mechanisms by which the organism expels, stores, or metabolically breaks down the contaminant. Compounds such as organochlorine pesticides and PCBs tend to accumulate in fatty tissues (lipophilic compounds), where they may remain for long periods of time. Animals in the upper levels of the food web may accumulate these compounds from prey until lipid storage sites are saturated. Their metabolism is then challenged to degrade and excrete the contaminants or their metabolic by-products, some of which are much more toxic than the original form. In this way, highly persistent and bioaccumulative compounds can magnify through the food web, having little noticeable toxic effect except at the highest trophic levels. Trace metals are also subject to bioaccumulation, but except for metal-containing organic compounds (e.g., methyl mercury) do not biomagnify in marine organisms.

Bioconcentration and biomagnification of toxicants pose particular risks to predators of fish, including birds, marine mammals, and humans. High concentrations of toxicants, such as PCBs and mercury, necessitate health advisories for frequent consumers of fish in some regions (EPA, 1999). Perhaps the most widely recognized effect of persistent contaminants on marine populations is the decline of populations of bald eagles and brown pelicans during the 1960s and 1970s. DDT and its breakdown products accumulated in adult birds from their prey, leading to changes in calcium metabolism in breeding females. The birds produced abnormally thin eggshells and ultimately experienced reproductive failures (Hickey and Anderson, 1968; Blus et al., 1971).

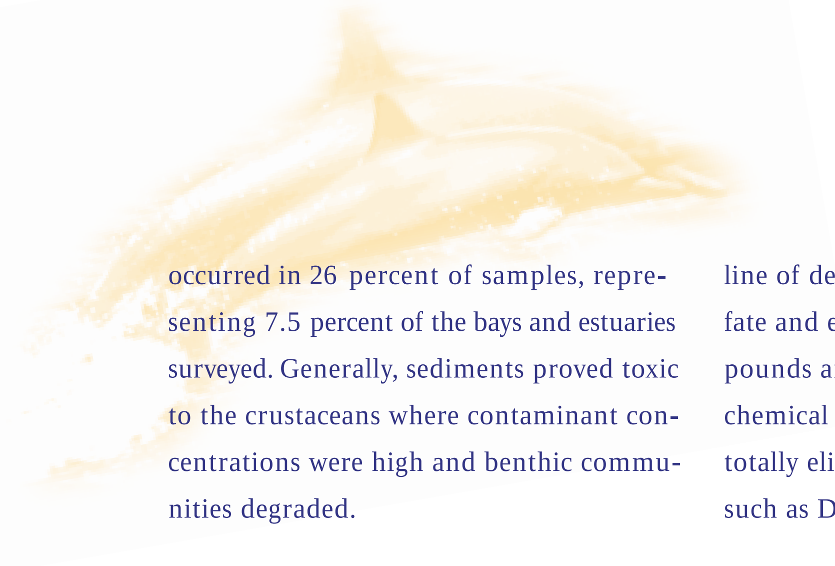
Extensive evidence demonstrates that toxicants can disrupt the metabolic, regulatory, or disease defense systems of an organism, eventually compromising its survival or reproduction. For example, genetic damage, malformations, and reduced growth and mobility were observed in Pacific herring embryos exposed to PAH (from weathered oil) levels as low as 0.7 ppb (Carls et al., 1999). Mollusks exposed to PCBs in New Bedford Harbor, Massachusetts, experienced both a loss of



reproductive output and increased susceptibility to disease (McDowell et al., 1999). Accumulation of PCBs and PAHs in Puget Sound rock sole has been correlated with reductions in spawning success (Johnson et al., 1998). Bioconcentration of PCBs has also been linked with impaired immune defenses that lead to disease and death in marine mammals, including seals and dolphins (Kuehl and Haebler, 1995).

Particular attention is currently being devoted to the disruption of endocrine systems by toxic contaminants. Some organochlorine pesticides, PCBs, dioxins, and other compounds functionally mimic or alter the production of hormones (NRC, 1999b). Tributyl tin (TBT), a biocide used in antifouling paints, has been shown to disrupt hormones controlling sexual development in mollusks exposed to concentrations as low as 10 parts per trillion, leading to irreversible reproductive abnormalities (e.g., females developing male sex organs) and reproductive failures (NRC, 1999b). Significant declines in marine snail populations have been documented in regions of North America and Europe where use of TBT was intense (Matthiessen and Gibbs, 1998; Nehring, 2000). Most uses of TBT paints in the U.S. were discontinued as a result of these findings. Feminization of males due to exposure to estrogen mimics and masculinization of females exposed to estrogen blockers have been observed in various animals, including mollusks, fish, reptiles, birds, and mammals (NRC, 1999b; Royal Society, 2000). For example, endocrine-disrupting chemicals have been implicated in the incidence of hermaphroditism in Norwegian polar bears and St. Lawrence beluga whales (De Guise et al., 1994).

Toxic substances in sediments appear to have localized effects in U.S. bays and estuaries and in certain offshore regions that received wastes, such as the New York and Southern California Bights. In the past decade, EPA's Environmental Monitoring and Assessment Program (EMAP) and National Sediment Quality Survey and NOAA's National Status and Trends Program have extensively measured the concentrations of contaminants in bottom sediments in the nation's bays and estuaries, collected collateral data on the communities of benthic organisms living in those sediments, and assayed toxicity of sediments to sensitive amphipod crustaceans. Using these three components—contaminant concentrations (and their probable effects based on an extensive database), the health of the communities living in the sediments, and experimental toxicity—Long (2000) concluded that biologically significant chemical contamination and toxic responses occurred throughout the nation's coastal waters, especially in the most urbanized and industrialized regions. Chemical concentrations exceeding guidelines for probable effects



occurred in 26 percent of samples, representing 7.5 percent of the bays and estuaries surveyed. Generally, sediments proved toxic to the crustaceans where contaminant concentrations were high and benthic communities degraded.

This three-pronged approach involving field studies does not fully resolve which contaminants and other factors are actually responsible for the toxicity and community degradation. The synergistic, additive, or antagonistic interactions among contaminants are poorly understood and challenging to assess, thus making it difficult to predict biological responses simply based on knowledge of the types and concentrations of contaminants present in a given area (Yang, 1998).

Pollution Abatement and Remediation

The most effective way to reduce the harmful impacts of toxic contaminants on marine ecosystems is to eliminate or restrict their use or production. The experiences with lead additives in gasoline, DDT, and PCBs show that in the long term this approach can reduce environmental concentrations and exposure for marine organisms. In addition to discontinuing the use or production of these substances, source controls, recycling and reuse, and other forms of "pollution prevention" provide the first line of defense (NRC, 1993a). Treatment and removal of pollutants from effluents and atmospheric emissions provide a second line of defense. Improved knowledge of the fate and effects of various classes of compounds and screening processes for new chemical products have reduced, but not totally eliminated, the risk of "surprises" such as DDT, PCBs, and TBT.

> "The most effective way to reduce the harmful impacts of toxic contaminants on marine ecosystems is to eliminate or restrict their use or production."

Legacy contaminants must be managed for decades to centuries into the future. Options include control of losses from waste sites and contaminated soils on land, treatment of urban stormwater, and remediation of contaminated sediments. Contaminated sediments exist in many ports, where they pose a risk of reintroduction of toxicants into the water column by physical disturbance of sediments or transferal through the food chain. Options for managing contaminated sediments include: leaving them in place to allow recovery to proceed through degradation and burial, capping them with clean sediments, treating them in place, and removing them for containment or treatment (NRC, 1997).

In the case of the pesticide kepone in the James River estuary, Virginia, the decision was to leave the contaminated sediments in place, and subsequent reductions of contaminants levels in the ecosystem and organisms were observed (NRC, 1997). However, when contaminant levels are high and the risks of reintroduction are great, capping may speed recovery of the ecosystem. The EPA has proposed placing clean sediments atop portions of the DDT deposits off Palos Verdes, California, in order to test the feasibility and effectiveness of this remediation method. Representatives of the DDT manufacturer have criticized this method because DDT concentrations in surface sediments have been declining and the process may expose heavily contaminated sediment below the surface (Whitaker, 2000). A similar controversy surrounds proposals to cap the dredged sediment disposal site in the apex of the New York Bight. These cases exemplify the dilemma faced in making decisions regarding remediation of contaminated sediments.

IV. The Challenge of Nutrient Pollution

Nutrient Overenrichment

An increase in the supply of organic matter in a water body is termed eutrophication (Nixon, 1995; see sidebar in Abstract). Over the last 30 years the discharge of organic wastes from municipal and industrial sources declined as a result of improved treatment. At the same time, eutrophication in many areas became more extensive due to increased loadings of mineral nutrients, particularly nitrogen and phosphorus, which stimulate the production of organic matter within the marine ecosystem. There are many consequences of this increased organic production, both beneficial and harmful. The latter include hypoxia, or stressfully low dissolved oxygen, reductions of seagrass beds and corals, and, potentially, noxious or toxic blooms of algae.

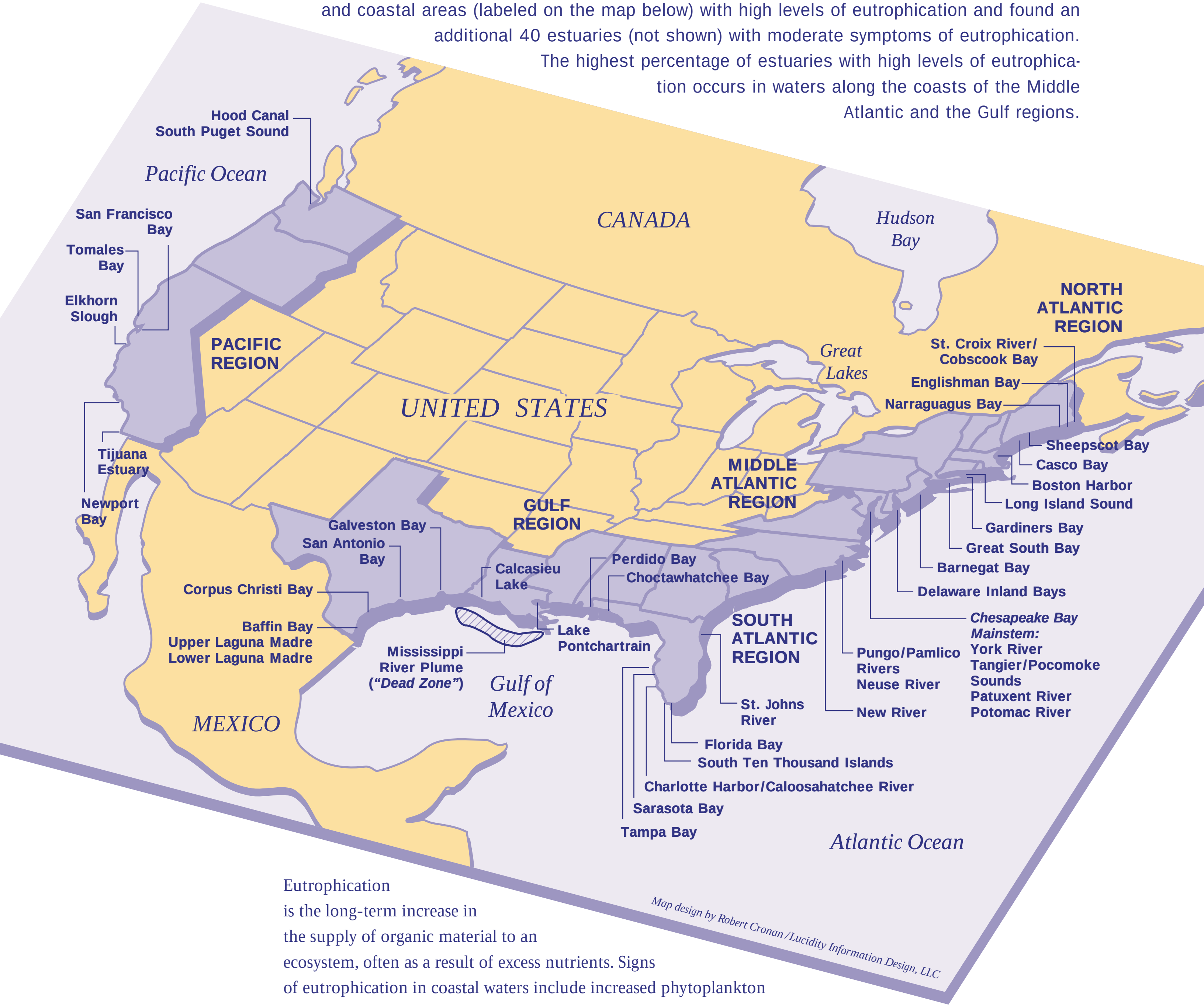
Nutrient pollution has been increasingly recognized as a key threat to coastal environments over the past 20 years because of both new scientific understanding and declining trends in water quality (Nixon, 1995). Loadings of nitrogen flowing in rivers to the Atlantic and Gulf coasts of the United States have increased four to eight fold from the time of European colonization (Howarth et al., 1996). Most of that increase came in the last half of the 20th century. Scientific research has demonstrated that nutrient overenrichment was a major contributor to the extensive changes observed in coastal ecosystems during that period. Three recent scientific assessments addressed nutrient pollution in U.S. coastal waters.

The National Oceanic and Atmospheric Administration characterized the symptoms of eutrophication for 138 bays and estuaries around the U.S. coast based on data review and expert consultations (Bricker et al., 1999). Approximately one-third of the water bodies had high expressions of eutrophic conditions (Figure 5). Altogether, 82 water bodies, representing 67 percent of the combined surface area of these bays and estuaries exhibited moderate to high degrees of depleted dissolved oxygen, loss of seagrasses, or harmful algal blooms. Moreover, it was predicted that eutrophic conditions would become more severe in 86 of these ecosystems by 2020. Systems having low inflow, poor flushing, or strong stratification are particularly susceptible to eutrophication. While this assessment was limited to estuaries and bays in the conterminous states, nutrient pollution has also resulted in loss of coral reef habitat and seagrasses in U.S. tropical regions (Bell, 1992; Lapointe, 1999). *(Continued on page 22)*

Figure 5

Areas of Significant Eutrophication in U.S. Coastal Waters

A recent National Oceanic and Atmospheric Administration (NOAA) study examined 138 estuaries along the coasts of the conterminous United States. A group of experts identified 44 estuaries and coastal areas (labeled on the map below) with high levels of eutrophication and found an additional 40 estuaries (not shown) with moderate symptoms of eutrophication. The highest percentage of estuaries with high levels of eutrophication occurs in waters along the coasts of the Middle Atlantic and the Gulf regions.



Map design by Robert Cronan/Lucidity Information Design, LLC

Eutrophication is the long-term increase in the supply of organic material to an ecosystem, often as a result of excess nutrients. Signs of eutrophication in coastal waters include increased phytoplankton growth, increased growth of macroalgae and epiphytes (plants that overgrow other plants), low dissolved oxygen, harmful algal blooms, and loss of seagrasses. Typically one or more of these symptoms is seen over large areas and/or persistently within the estuary. The "Dead Zone" in the Gulf of Mexico refers to an extensive area of seasonal hypoxia, or depletion of dissolved oxygen, in the bottom waters.

Adapted from Bricker et al., 1999.

Box 4

Gulf of Mexico's "Dead Zone"

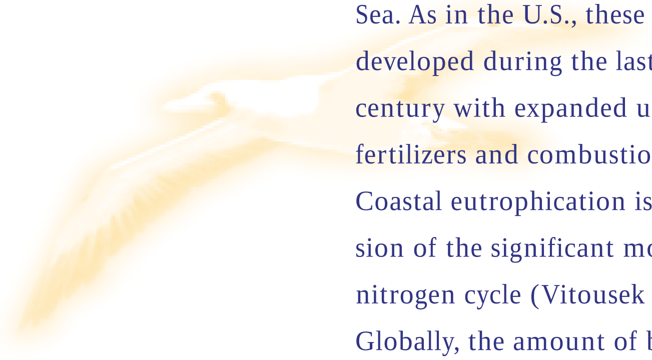
In a large region of the inner continental shelf off the coast of Louisiana and Texas, the bottom water oxygen levels fall too low (<2 mg/L) to support fish, crustaceans, and many other invertebrates during the warmer months of April to September. This hypoxic zone, or Dead Zone, has been as large as 12,000 square miles (20,000 km^2) but varies in dimensions from year to year and within years, depending on river runoff, and meteorological and oceanographic factors. A recently completed integrated assessment conducted under the auspices of the President's National Science and Technology Council (CENR, 2000) concluded that:

1. the hypoxia is caused primarily by excess nutrient runoff (particularly of nitrogen) from the Mississippi-Atchafalaya River Basin in combination with stratification of Gulf waters;
2. landscape alterations and river channelization during the late 19th century and first half of the 20th century reduced the river basin's hydrologic buffering capacity;
3. eutrophication and hypoxia increased during the latter half of the 20th century during which the flux of nitrate-nitrogen almost tripled (between 1955–1970 and 1980–1996), concomitant with the rapid increase in the use of chemical fertilizers;
4. about 90 percent of the nitrate load comes from diffuse sources, particularly from agricultural lands along the upper Mississippi and Ohio rivers, nearly 1000 miles upstream from the river's mouth; and
5. Gulf ecosystems and fisheries are affected by hypoxia, but economic impacts are difficult to quantify.

Models predicted significant reductions in hypoxia would occur with a 20 to 30 percent nitrogen load reduction. Two approaches are required to achieve that level of reduction: (1) improved agronomic practices that reduce nitrogen losses from farm fields and (2) trapping nitrogen lost from fields in restored wetlands, vegetated buffers, reconnected floodplains, and coastal wetlands. These recommendations have been met with considerable controversy regarding both the certainty of the science and the costs and impacts on food production among midwestern states and agricultural interests. In October 2000, a task force including senior policymakers from eight federal agencies, nine states, and two tribal governments set a general goal to reduce the average area experiencing hypoxia to less than 5,000 km^2 (1,930 square miles or about 40 percent of its average dimensions during the 1990s), which the task force recognized would probably require the reduction of nitrogen inputs by 30 percent.

The President's National Science and Technology Council produced an integrated assessment of large-scale hypoxia in the northern Gulf of Mexico (CENR, 2000) (Box 4). The assessment concluded that diffuse sources of nutrient pollution have caused more extensive hypoxia, covering up to 12,000 square miles of the northern Gulf continental shelf, since the 1950s. It identified more efficient use of fertilizers and restoration of wetlands in the river basin as effective means to reduce the extent and severity of hypoxia in the Gulf.

Finally, the National Research Council (2000a) recently published an in-depth evaluation of the causes and effects of overenrichment in coastal waters and of abatement strategies, including monitoring and modeling, goal setting, and source reduction and control. Noting the substantial adverse impacts of nutrient pollution and the likelihood that nutrient loads will increase as human populations grow, the NRC calls for a nationwide strategy for reducing impairment by nutrient pollution and protecting unimpaired waters. One goal suggests a 10 percent reduction by the year 2010 in the number of coastal water bodies demonstrating severe impacts and a 25 percent reduction by 2020.



Large-scale eutrophication has also occurred in seas around other developed nations, including the Baltic Sea, eastern North Sea, northern Adriatic Sea, northwestern Black Sea, and Japan's Seto Inland Sea. As in the U.S., these problems also developed during the last half of the 20th century with expanded use of chemical fertilizers and combustion of fossil fuels. Coastal eutrophication is but one dimension of the significant modification of the nitrogen cycle (Vitousek et al., 1997). Globally, the amount of biologically available nitrogen added to the biosphere each year has more than doubled the amount made available by the natural sources of plant fixation and lightning. In addition to impacts on marine ecosystems, acid rain, loss of forest soil fertility, emissions of nitrous oxide (a greenhouse gas), and reduction of plant biodiversity are other consequences of the increasing flow of biologically available nitrogen in the biosphere.

Consequences for Living Marine Resources

Nutrients are generally in short supply in most ecosystems and microscopic and macroscopic plants have adapted mechanisms to assimilate them and grow when they are available. The addition of nutrients to an ecosystem affects not only how fast plants grow but also which plants grow most rapidly. These responses are affected by many factors, including light, temperature, mixing and stratification of the water column, the ratio of the various nutrients, and grazing by animals. In marine ecosystems, the rate at which plants create new organic matter (primary production) is closely related to nitrogen inputs (NRC, 2000a). Primary production doubled from the beginning of the 1960s to 1990 in the southern Kattegat between Denmark and Sweden (Richardson and Heilman, 1995), one of the few areas where primary production has been consistently measured. Similar dramatic increases in primary production in the Chesapeake Bay (Cooper, 1995) and the northern Gulf of Mexico (Rabalais et al., 1996) have been inferred based on chemicals and fossils laid down in bottom sediments.

Although much of the increased organic matter is consumed by zooplankton, bacteria, and bottom filter feeders, the amount of organic matter that falls to the bottom in the form of dead plant cells and fecal matter from grazing organisms is also increased. This changes the food regime of organisms living on the bottom or within bottom sediments, initially increasing the abundance of animals and microorganisms that consume the rich organic deposits. However, the respiration of these decomposer organisms consumes oxygen. At first oxygen is depleted in bottom sediments and, if organic loading is heavy enough, the deficit of oxygen reaches into the water column above the seabed. The severity and persistence of resulting hypoxia depend on the stratification of the water column. Less dense (warmer or fresher) surface waters overlying more dense (colder or saltier) bottom waters, with little mixing between the layers, prevents supplies of oxygen from surface waters from replenishing the oxygen consumed by decomposers.

Severe hypoxia near the bottom has become a more regular and extensive seasonal phenomenon in ecosystems such as the Louisiana continental shelf (Rabalais et al., 1996), Chesapeake Bay (Boesch et al., in press), the western basin of Long Island Sound (Long Island Sound Study, 1998), and many other parts of the world (Diaz and Rosenberg, 1995).

As bottom oxygen is depleted, many organisms unable to swim away succumb. Crustaceans, echinoderms, and mollusks are particularly sensitive to the lack of oxygen and the hydrogen sulfide that emanates from putrefying sediments. Consequently, benthic communities experiencing eutrophication and hypoxic stress are altered and have less species diversity. Substantial changes in the production and composition of benthic communities may be evident well before severe hypoxic conditions occur in overlying waters (Diaz and Rosenberg, 1995).

Hypoxic conditions in waters above the seabed force fish and swimming invertebrates to avoid the stressful conditions. Catches of fish and shrimp in bottom trawls in the Gulf of Mexico are dramatically lower or nonexistent where bottom dissolved oxygen levels fall below 2 mg/L (CENR, 2000). Fish and crustaceans often move up in the water column, where they are more susceptible to predation. Hypoxia can also block normal onshore-offshore migration. Despite these apparent obstacles to survival, large-scale hypoxia has not decimated the important shrimp fisheries of the northern Gulf of Mexico (CENR, 2000), although it may have reduced the catch of brown shrimp (Zimmerman and Nance, in press). Many other factors affect shrimp populations, rendering less-than-catastrophic effects due to hypoxia difficult to detect. Bottom hypoxia has resulted in declines in the catches in demersal (living near the bottom) fisheries in Europe and Japan (Caddy, 1993, 2000).

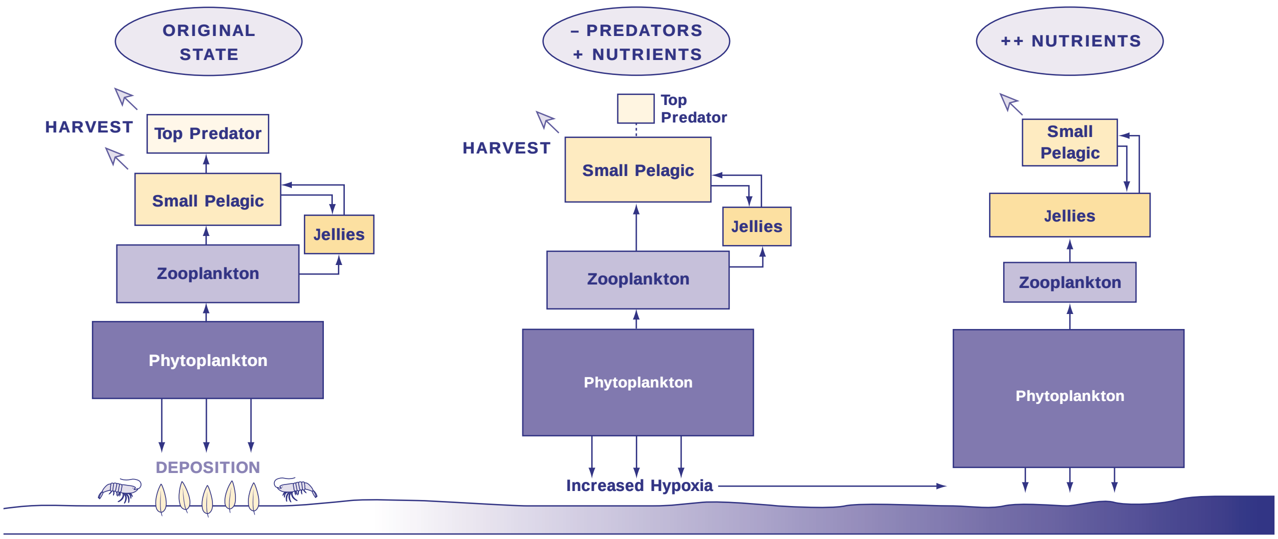
"Hypoxic conditions in waters above the seabed force fish and swimming invertebrates to avoid the stressful conditions."

Nutrients are necessary to support the productivity of marine food webs. Across the full range of marine ecosystems, the supply of nutrients—particularly nitrogen—is positively correlated with fisheries yield (Nixon et al., 1986). Although the general relationship is undeniable, the strength of coupling between nutrients and the production of animals within a given ecosystem has been called into question (Micheli, 1999). Nonetheless, increases in the catch of some fisheries have been observed in the North and Baltic Seas and Seto Inland Sea in Japan, concurrent with increases in nutrient loading (Caddy, 1993). While some increases are attributable to increased fishing pressure or more efficient fishing paralleling increased nutrient loadings, greater yields appear to be at least in part due to nutrient stimulation of the food chains supporting the fisheries. Other factors can affect fisheries yield, however, including climatic variation and the effects of fishing itself on the food chain. There is a strong global trend of “fishing down the food chain,” wherein fishing is targeted on smaller species once stocks of higher predators are depleted (Pauly et al., 1998). Under these conditions there is less predation on mid-trophic level species, allowing them to become more abundant. These factors may result in increased yields measured as biomass, but the economic value of the fishery is typically smaller.

Eutrophication combined with increased fishing intensity, results in higher yields of small pelagic (living in the water column) species and reduced yields of top

Figure 6

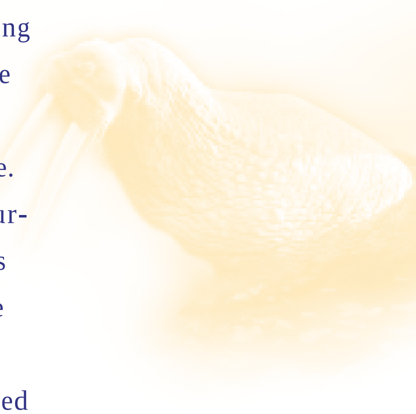
imultaneous Effects of Eutrophication and Fishery Harvest on Marine Food Chains



ource: Caddy, 2000.

predators and demersal (living near the bottom) species (Figure 6). In the extreme case, severe hypoxia and highly enriched food chains favor gelatinous predators (jellyfish and comb jellies) and result in the virtual elimination of demersal resources and reduction in small pelagic fish stocks (e.g., anchovies in the Black Sea). European seas can be ordered based on relative harvests of demersal and pelagic fisheries from the Irish Sea, with low nutrient inputs and proportionally greater demersal fisheries, to the Adriatic and Black Seas, with high nutrient inputs and predominantly pelagic fisheries (Caddy, 2000). In the U.S., enriched systems such as the Chesapeake Bay and northern Gulf of Mexico exhibit high yields of a small pelagic fish (menhaden). These systems have also experienced overharvesting of top predators such as striped bass, red snapper, and red drum and face current management problems for demersal crustaceans such as blue crabs and penaeid shrimp. The interactions between fishing pressure and eutrophication require that fisheries resources be managed not only in a multispecies context but also within an ecosystem framework. That framework may need to take into account human activities and natural processes extending even into the watersheds that deliver fresh water and nutrients to the sea (Caddy, 2000).

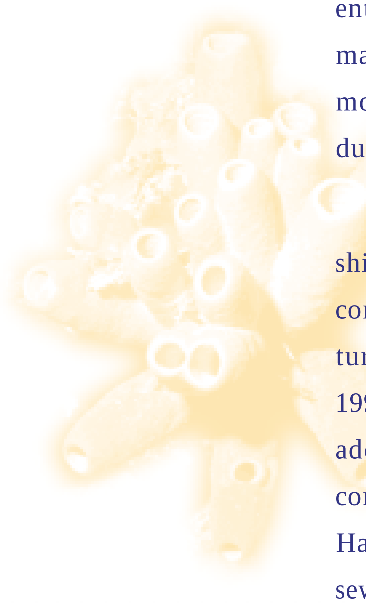
Seagrasses, seaweeds, and coral reefs create important habitats that provide food and shelter for a rich diversity of marine organisms, but are very sensitive to nutrient pollution. High nutrient levels in the water column can stimulate luxuriant growth of seagrass leaves, but there is insufficient rhizome growth to tide the plants over during periods of reduced photosynthesis. Reductions in available light caused by increased phytoplankton density and the proliferation of microscopic and macroscopic algae growing on seagrass blades also adversely affect the plants (Duarte, 1995). Seagrasses sometimes give way to fast growing macroalgae. Ultimately, conditions may become too turbid to support any macroscopic plants. As seagrass beds are lost, sediments are more easily eroded, causing the pace of loss to accelerate. Significant seagrass losses caused by excessive nutrient loadings have been observed in bays and coastal lagoons in New England, the mid-Atlantic region, Florida, Texas, and California (Bricker et al., 1999), as well as in Europe, Australia, and Japan (Duarte, 1995). On the other hand, partial recovery of seagrass beds in Sarasota, Tampa, and Chesapeake Bays has been observed as a result of efforts to abate nutrient pollution.



In the Baltic Sea, shallow rocky areas once covered with brown seaweeds that provide important spawning sites for fishes changed to a plant community dominated by rapidly growing green algae of little habitat value (Jansson and Dahlberg, 1999).

In the northwestern Black Sea, an extensive meadow of red algae covering 4,000 square miles in the 1950s was reduced to 200 square miles by the 1990s, causing a loss of a harvested resource, the disappearance of a unique fauna, and reduction in an important source of oxygen (Zaitsev, 1999).

Reef-building corals have a symbiotic relationship with algae (zooxanthellae) that live in coral tissue and efficiently recycle available nutrients. This relationship allows corals to build reefs in clear waters with low nutrient levels. Even small increases in nutrient loads can stimulate phytoplankton and reduce light availability for zooxanthellae in the deeper parts of the reef. Elevated nutrient levels or reduced light availability may make already temperature-stressed corals more prone to expelling zooxanthellae, producing a “bleaching” effect (Brown, 2000).



Increased availability of nutrients can shift an ecosystem dominated by corals and coralline algae toward dominance by algal turf and macroalgae (Bell, 1992; Lapointe, 1999). Nutrient stimulation due to sewage additions was responsible for overgrowth of coral reefs by macroalgae in Kaneohe Bay, Hawaii, during the 1960s. Redirecting sewage out of the bay reversed this situation (Smith et al., 1981). Grazing animals normally prevent algal overgrowth, so when overfishing reduces grazers, reefs may be particularly susceptible to nutrient pollution (Lapointe, 1999). Overenrichment may also contribute to environmental stresses that make corals susceptible to diseases that appear to be increasing in distribution and virulence (Harvell et al., 1999). Finally, a recent study in Barbados found that boring sponges, which weaken coral structures, were more common in reefs experiencing eutrophication (Holmes, 2000).

Probably no effect of nutrient pollution has captured more public attention than harmful algal blooms, though, in fact, the causes of these blooms are complex and incompletely understood. Harmful blooms involve a variety of unicellular organisms that create nuisance conditions in high concentrations, cause mass mortalities of marine organisms, or illness—or even death—in humans (Smayda, 1997). Included are microscopic organisms (including red tides, brown tides, and the notorious phantom dinoflagellate, *Pfiesteria piscicida*) that result in shellfish poisoning of humans, cause fish kills, and jeopardize aquaculture operations. The distribution, incidence, and severity of harmful algal blooms have been rising in recent decades, not only in the United States but also in Europe, Japan, and China (Hallegraeff, 1993). While nutrient pollution is clearly not the cause of some blooms, in other cases there is evidence that changes in nutrient supplies and ratios are a contributing factor (NRC, 2000a).

The chemical form and relative ratios of available plant nutrients can cause shifts in phytoplankton composition and unusual algal blooms. Organic nitrogen seems to favor the organism causing brown tides and possibly *Pfiesteria* in mid-Atlantic bays. A shortage of silicon, a nutrient needed for diatom growth, relative to the supplies of nitrogen and phosphorus favors the growth of flagellated phytoplankton, some species of which are toxic (NRC, 2000a). Even if the species favored are not toxic, changes in the proportions of various nutrients delivered to coastal waters could change the type as well as the amount of phytoplankton that grows, with significant consequences throughout the food web. Inputs of silicon from land have declined in many regions as a result of sediment entrapment behind dams, while phosphorus inputs have remained steady and nitrogen inputs have increased (Justić et al., 1995; CENR, 2000).

Eutrophication usually results in reductions in species diversity of the affected ecosystems and, if extensive and severe, can impact biodiversity on a regional scale. In the northwestern shelf of the Black Sea, for example, only one-third as many benthic animal species could be found within a given depth zone in the 1980s as were found in the 1960s (Diaz and Rosenberg, 1995). There is at this point no evidence that eutrophication is threatening the global extinction of any species. However, by isolating distinct subpopulations, local extinction of a species in one or two estuaries along a coast could affect the genetic flow within the regional population (NRC, 1995).

Eutrophication can also adversely affect the services provided by marine ecosystems. Nutrient removal by denitrification and burial in bottom sediments may be one of the most important services provided by coastal ecosystems (Costanza et al., 1997). However, when severe seasonal hypoxia occurs, both phosphorus and ammonia are released from bottom sediments, turning an important sink for nutrient pollution into a source—thereby fueling more hypoxia (Boesch et al., in press). Through this and other feedback mechanisms, eutrophic ecosystems appear to be less resilient, i.e., they have less capacity to buffer changes and recover from disturbances more slowly.

"Eutrophication usually results in reductions in species diversity of the affected ecosystems and, if extensive and severe, can impact biodiversity on a regional scale."

Sources and Trends

Human activities have increased the flow of phosphorus to the world's ocean by a factor of three over natural rates and the flow of nitrogen to U.S. coastal waters by four to eight times (NRC, 2000a). The largest human-controlled addition of nitrogen to the environment is the manufacture of inorganic nitrogen fertilizer. However, other activities, including the combustion of fossil fuels and cultivation of nitrogen-fixing crops, also convert atmospheric nitrogen into reduced, oxidized, or organic forms that are more biologically available than the gaseous nitrogen that comprises most of the air we breathe. About 20 percent of the fertilizer nitrogen applied in North America leaches into waters and 65 percent is removed in crops (NRC, 2000a). Most of the crops (70 percent) are fed to animals rather than humans; thus the amount of nitrogen reaching water bodies from animal wastes probably exceeds that from fertilizer runoff. Ammonia released into the air from animal wastes can be an important pathway though which nitrogen reaches coastal waters (Box 5). Human sewage is also an important avenue for nitrogen originally contained in crops or meat to reach coastal waters.

The relative importance of the sources of nutrients varies greatly among U.S. coastal regions, depending on the characteristics of their drainage basins, human populations, intensity of agricultural activities, and amount of atmospheric deposition. The percentages in Figure 7 are based on relating source estimates to fluxes measured through stream monitoring. Other statistical analyses across many watersheds (NRC, 2000a) suggest that atmospheric sources are a somewhat more significant contributor to diffuse source inputs than shown here, but the interregional differences depicted are in any case similar. Direct discharges of sewage dominate nitrogen inputs in northeastern bays; otherwise diffuse sources predominate. Agricultural sources generally are

Box 5

Ammonia Emissions: An Emerging Issue

Atmospheric deposition of nitrogen has been considered primarily in terms of the nitrogen oxides (NO_X) produced by fossil-fuel combustion. However, recent evidence shows that ammonia emissions from agricultural operations can be a significant pathway for nitrogen inputs to coastal waters, accounting for as much as half of the total nitrogen deposition in regions with extensive livestock production (Walker et al., 2000).

In the Chesapeake Bay watershed, agricultural livestock contribute an estimated 81 percent of the annual atmospheric burden of ammonia (Chimka et al., 1997). Ammonia volatilizes from animal wastes in feeding operations, waste-storage facilities, and land application of manure. Increases in deposition of ammonia have occurred with expanding animal production. For example, a 60 percent increase in ammonia wet deposition was observed on the Delmarva Peninsula during the past two decades when this region experienced a 20-fold increase in poultry production (Scudlark and Church, 1999). In eastern North Carolina, ammonia wet deposition more than doubled over the same time period (Paerl and Whitall, 1999) in a region in which swine production tripled during the last ten years (Mallin, 2000).

Ammonia emissions also occur from various urban sources, including combustion, POTWs, and chemical plants. Recent modifications to gasoline-powered vehicles designed to reduce NO_X emissions (i.e., three-way catalytic converters running rich air-fuel conditions) actually increase ammonia emission rates (Fraser and Cass, 1998).

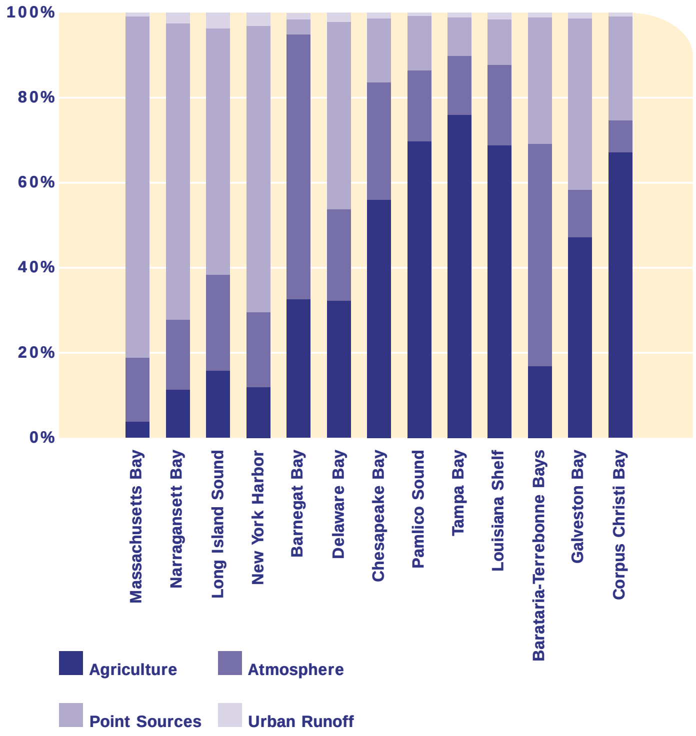
most important from the Chesapeake Bay south, while atmospheric sources are greater than agricultural sources in the Northeast.

Although global additions of nitrogen to the biosphere are continuing to increase rapidly (Vitousek et al., 1997), current trends in nitrogen loadings to U.S. coastal waters are in aggregate generally stable or growing slowly (NRC, 2000a), while inputs of phosphorus are stable or declining. Although the worldwide use of chemical fertilizers is growing and projected to increase substantially to support an expanding world population and increased meat consumption (Forsberg, 1998), the use of chemical fertilizers in the U.S. nearly plateaued in the 1980s (NRC, 2000a). However, increased inputs of both nitrogen and phosphorus have occurred in regions of the country experiencing an expansion and intensification of animal-feeding operations or human population growth. Future consumption of fertilizers and generation of animal wastes in the U.S. could increase, depending on global market forces. Atmospheric deposition of nitrogen from combustion of fossil fuels in vehicles and power plants has stabilized over much of the country as a result of pollution controls imposed under the Clean Air Act, and future efforts to improve air quality should result in reductions (EPA, 2000c).

Population growth increases the amount of sewage generated—a problem for rapidly growing parts of the country.

Figure 7

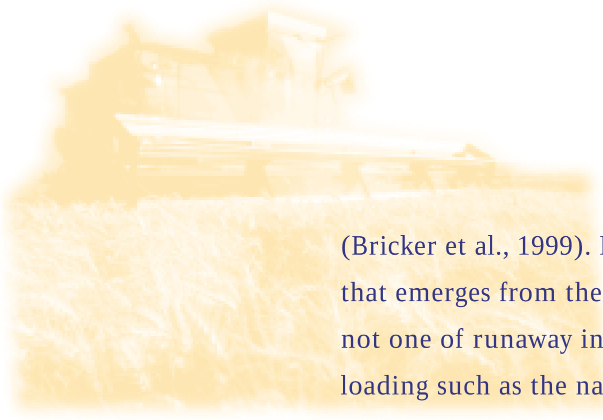
Estimated Nitrogen Loadings to Selected Atlantic and Gulf Coast Bays and Estuaries and Their Sources



Source: Castro et al., 2000.

However, where eutrophication is a recognized problem, implementation of advanced nitrogen removal technologies in POTWs can keep pace with population increases. In many coastal regions of the U.S., however, the rate at which land that produces relatively little nutrient runoff is converted into suburban development, roads, and parking lots—which increase water and nutrient runoff—has been progressing much faster than that of population growth.

The NOAA national eutrophication assessment estimated that eutrophic conditions are likely to worsen in two-thirds of the bays and estuaries examined



(Bricker et al., 1999). However, the prospect that emerges from the preceding analysis is not one of runaway increases in nutrient loading such as the nation experienced between 1960 and 1990, but one of stability or slower growth. This offers the real potential for substantial reductions with aggressive application of technologies. This outlook varies, of course, among regions, and coastal population growth near presently unaffected but susceptible bays and estuaries could greatly increase nutrient pollution in those areas. One should not infer from this that nutrient pollution is no longer a serious problem. The effects of eutrophication on coastal ecosystems are severe and widespread, making its abatement worthwhile, while at the same time challenging.

Pollution Abatement

Significant reduction in nutrient pollution may be achieved by approaches that: (1) reduce the use of the nutrients in the first place; (2) control losses to the environment at the point of release (e.g., farm field, animal feeding operation, lawn or subdivision, vehicle, power plant, or POTW); and (3) sequester or remove pollutants as they are transported to the sea.

Phosphorus can be almost completely removed from wastewaters by additional chemical and biological treatment. Phosphorus removal from discharges into the Potomac estuary below Washington, D.C., produced substantial improvements in water quality and living resources (Jaworski, 1990). Significant nitrogen removal has been achieved in Chesapeake, Tampa, and Sarasota Bays by biological nutrient removal—a process in which one group of microorganisms convert wastewater ammonia to nitrate and another converts nitrate to nitrogen gas (NRC, 1993a, 2000a).

Reductions in nitrogen oxide (NO_X) emissions to the atmosphere have been driven by air quality considerations generally outside the influence of water quality or coastal ecosystem managers. For example, in 1987 the Chesapeake Bay Program established a goal to reduce the controllable nitrogen inputs by 40 percent, but specifically excluded atmospheric deposition from the sources considered “controllable.” Nitrogen oxide emissions from power plants and vehicles are regulated under the Clean Air Act (CAA); a key goal of the 1990 amendments of the act is to reduce ground-level ozone that poses human health risks and stresses forests and crops. Significant reductions in NO_X emissions from stationary and mobile sources are in the offing to meet CAA requirements. The EPA estimates that a 40 percent reduction in NO_X emissions can ultimately be achieved as a result of new standards, technologies, and efficiencies being pursued under the Clean Air Act. Atmospheric deposition of nitrogen may be far more “controllable” than previously thought.

Abatement of agricultural sources of nutrient pollution may prove to be a more difficult challenge. To be practical, abatement of agricultural sources of nutrients must focus not only on reducing fertilizer use but also on plugging the many leaks in agricultural nutrient cycles. Efficiencies in fertilizer use in U.S. agriculture, measured by the ratio of nitrogen in harvested crops to nitrogen in fertilizer applied, have been slowly but steadily increasing since the mid-1970s (Frink et al., 1999). Nevertheless, about one-third of the nitrogen applied is not recovered in harvested crops (NRC, 2000a). Not all of the missing nitrogen contributes to eutrophication of coastal waters. Much is denitrified in soils or aquatic systems en route to the sea or is stored in soils or groundwater. In addition to increasing the efficiency of nitrogen uptake by crops, the return of nitrogen gas to the atmosphere can be enhanced through management practices.

Various agricultural practices affect nitrogen and phosphorus runoff and losses to groundwater (which ultimately seeps into surface waters). Practices employed to reduce soil erosion, such as contour plowing, timing of cultivation, conservation tillage (little or no tilling), stream-bank protection, grazing management, and grassed waterways also reduce nutrient pollution. Other practices are more specifically targeted to the efficient use and retention of nutrients: (1) soil testing to precisely match fertilizer applications to crop nutritional needs (many farmers still overapply to ensure maximum crop yields); (2) applying fertilizer only at the time the crop needs it; (3) crop rotation; (4) planting cover crops in the fall; (5) using soil and manure amendments; and (6) specialized methods of application (NRC, 1993b, 2000a). Landscape practices such as maintaining buffer strips between cultivated fields and nearby streams, moderating excessive drainage by ditches and tile lines, and maintaining wooded riparian areas can further reduce the leakage of agricultural nutrients to surface waters. By combining these approaches a significant portion of the edge-of-field nitrogen losses can be reduced (Boesch and Brinsfield, 2000).

Often, animal wastes are the most significant source of nutrient pollution from agriculture. Although the total production of livestock in the U.S. has not dramatically increased in recent years, the number and size of concentrated animal feeding operations have. Enclosures or trapping devices may eventually be required to stem ammonia emissions from animal wastes. Manure management also presents a risk of pollution if holding facilities fail or do not function properly (Mallin, 2000). Finally, frequently too much manure is produced within a geographic area for it to be applied to nearby land without overloading soils with nutrients (NRC, 2000a).

"Significant reductions in NO_X emissions from stationary and mobile sources are in the offing to meet CAA requirements."

Urban runoff can also be an important diffuse source of nutrients. Reduction and control of urban and suburban diffuse sources can be achieved through: (1) reductions in the use of fertilizers; (2) effective and well-maintained stormwater collection systems (retention ponds can remove 30 to 40 percent of the total nitrogen and 50 to 60 percent of the total phosphorus); and (3) improved septic systems that promote denitrification (NRC, 2000a). Preservation and restoration of riparian zones and streams within urban and suburban areas is also an important aspect of effective nutrient control. However, the ability of streams to function effectively in nutrient removal is compromised when a significant portion of their watersheds is covered by impervious surfaces and the amplified runoff scours the streambeds (Booth and Jackson, 1997).

"Geographically targeting riparian and wetland restoration is critical to its effectiveness in nutrient control."

Removing or sequestering pollutants as they are transported downstream can also abate nutrient pollution. Many American watersheds were once sponge-like, containing extensive floodplains and wetlands that slowed the flow of water and served as sinks for dissolved and suspended nutrients. However, well over half of the wetlands present in the conterminous United States at the time of European settlement have been converted to other land uses and the percentage of inland swamps and riparian wetlands lost is even greater (Mitsch and Gosselink, 2000). Many floodplains have been disconnected from their rivers by flood-control projects or agricultural conversion and no longer serve as nutrient sinks.

Reducing and controlling diffuse sources of land runoff must involve large-scale landscape management, including restoration of riparian zones and wetlands (NRC, 1999c). The integrated assessment of hypoxia in the Gulf of Mexico estimated that 5 million acres of restored wetlands in the Mississippi River Basin would reduce nitrogen loading to the Gulf by 20 percent. Coupled with feasible controls in agriculture, this would achieve a nearly 40 percent reduction in nitrogen delivered to the Gulf. Similarly, the Chesapeake Bay Program is striving to reforest 2,000 miles of riparian zones and restore 25,000 acres of wetlands by 2010 in order to achieve nutrient-reduction goals (Boesch et al., in press).

Geographically targeting riparian and wetland restoration is critical to its effectiveness in nutrient control. Statistical models based on water quality measurements throughout the Mississippi River Basin show that the percentage of nitrogen leached from a field that reaches the Gulf of Mexico depends greatly on its proximity to larger streams and rivers (Alexander et al., 2000). Biological uptake and denitrification are already effective in small watercourses; therefore restoration of riparian and wetland habitats along moderate to large streams should be more cost-effective. However, because of equity considerations, both incentives (subsidies and cost sharing, technical assistance, and insurance) and disincentives (regulatory controls, taxes, and fees) for abatement tend to be applied uniformly.

Watershed Approaches

A given body of coastal water (bay, estuary, or continental shelf region) receives nutrients from numerous sources; thus an integrated strategy for effective abatement of nutrient pollution is required. Because of the importance of diffuse sources, the strategy should encompass the catchment basin, or watershed, draining into the coastal waters. Moreover, it may have to consider nutrients originating outside the watershed but

Box 6

Nonpoint Sources: Acts and Actions

Provisions of both the Clean Water Act (CWA) and Coastal Zone Management Act (CZMA) address diffuse, or nonpoint, sources of nutrient pollution; however, neither law has been very effective in controlling these sources. The implementation of provisions has been poorly funded, and arguably too much discretion is granted to states and local authorities (Adler, 1995; Johnson, 1999). A central programmatic shortcoming is the fundamental difficulty of influencing local land uses in order to obtain water-quality objectives. Under Section 208 of the 1972 CWA amendments, states were provided support and wide latitude in developing regional plans that identified point and nonpoint sources of pollution and methods, including land-use requirements, to control the sources (Anderson, 1999). However, the plans developed proved difficult to implement (Adler, 1995).

Section 319 of the 1987 CWA amendments requires the states to report on waters where nonpoint sources are problematic and identify best management practices and programs for source control. Section 319 moved toward, if not fully embraced, a watershed approach. State participation remained voluntary and EPA did not require states to penalize nonpoint-source polluters failing to adopt best management practices (Johnson, 1999). Lack of authority, enforcement, and monitoring clearly limited the effectiveness of the 319 efforts (Ruhl, 2000; Anderson, 1999).

In 1990 the reauthorized CZMA included Section 6217, under which states were required to implement enforceable policies to control nonpoint sources affecting coastal waters. Plans were originally required by 1995, but difficulties in implementation and coordination arose. Greater flexibility in plans was allowed and the period of implementation was extended to 15 years (NOAA, 2000).

Section 303 of the CWA requires the determination of a total maximum daily load (TMDL) of pollutants, including those from nonpoint sources, that can be accommodated by an impaired water body in order for it to meet water-quality standards for its designated use (Healy, 1997). A waste-load allocation then apportions the TMDL among the sources. This provision was not applied until lawsuits in the 1990s mandated EPA to establish TMDLs. Technical difficulties in determining TMDLs, legal issues regarding allocating loads among the sources, and the weak authority to regulate nonpoint sources remain serious barriers (Ruhl, 2000). Meanwhile, Congress prohibited EPA expenditures on further implementation of TMDLs during Fiscal Year 2001 (Copeland, 2000).

transported into it through the atmosphere. These are nonconventional units for ocean and coastal resource management and pose numerous challenges.

"Monitoring is critical in determining the effectiveness of abatement strategies, evaluating responses of the ecosystem, and placing these responses in the context of ecosystem variability."

Recognition of the importance of diffuse-source pollution within a watershed is not new. Federal water-quality and coastal-management statutes include provisions for the assessment and control of nonpoint source pollution (Box 6), but to date they have been largely ineffective in limiting or reversing nutrient pollution of coastal waters. Their implementation has been long on planning and short on actions needed to control diffuse sources. In addition to the difficulties in determining management goals, acceptable nutrient loads, and efficient and equitable allocations among sources, substantial reliance on voluntary rather than mandatory reductions of diffuse sources has constrained the effectiveness of source-reduction efforts (NRC, 2000a).

These shortcomings are evidenced by the fact that 44 percent of the estuarine area assessed in 1998 did not fully meet the standards to support the designated uses (EPA, 2000a). Pathogens, organic enrichment, low dissolved oxygen, municipal point sources, urban runoff, and atmospheric deposition were the primary reasons, and diffuse-source pollution was a common culprit.

Concerted efforts to reverse nutrient pollution have been undertaken in some watersheds. In 1987 Pennsylvania, Maryland, Virginia, the District of Columbia, and the federal government committed to a 40 percent reduction in the “controllable” inputs of both nitrogen and phosphorus into the Chesapeake Bay by the year 2000. At about that same time, commitments were also being made for reductions of 50 percent of nutrient inputs into the North and Baltic Seas (Boesch and Brinsfield, 2000). Current estimates for the Chesapeake are that a 34 percent reduction in controllable phosphorus and a 28 percent reduction in controllable nitrogen will have been achieved by the end of 2000 (equivalent to 31 and 15 percent of the total loads, respectively; Blankenship, 2000). These are model simulations, but significant reductions in nutrient concentrations in rivers flowing into the Chesapeake Bay and in point-source discharges have been documented (Boesch et al., in press). These gains for the Chesapeake and European waters indicate that a watershed approach to reducing nutrient pollution can work, but so far successes have relied disproportionately on point-source controls. Under a new Chesapeake Bay agreement, more significant load reductions necessary to attain water-quality goals are being determined through a TMDL process (Box 6). Achieving these reductions will require a more rigorous effort to control diffuse sources.

Nitrogen inputs to Tampa Bay have also been reduced, again largely as a result of advanced treatment of sewage. Seagrass beds showed some recovery as a result (Lewis et al., 1998). A decrease in anthropogenic nitrogen inputs of 58.5 percent is the management goal for Long Island Sound (Long Island Sound Study, 1998). Direct discharges dominate nutrient sources there, thus biological nutrient removal at POTWs—at an estimated capital cost of more than 300 million dollars—is being counted on for most of this reduction.

Watershed approaches are being pursued in controlling diffuse sources of nutrients and other pollutants in many other U.S. bays and estuaries. In most, voluntary approaches to the pollution abatement are preferred; however, regulatory approaches are becoming more necessary, particularly as a result of the TMDL process (NRC, 2000a).

Watershed approaches place a premium on environmental modeling and monitoring (NRC, 2000a) in an adaptive management framework (Lee, 1993; CENR, 2000). Models are needed to track sources through the watershed, target abatement, and relate pollutant inputs to marine ecosystem responses. Monitoring is critical in determining the effectiveness of abatement strategies, evaluating responses of the ecosystem, and placing these responses in the context of ecosystem variability.

V. Implications for National Ocean Policy

Pollution in Context

Determining the degree to which pollution affects marine living resources, biodiversity, and ecosystem services and comparing these effects to those due to fishing, habitat modification, and global climate change are extremely difficult. Effects of pollution must be separated from those due to natural variability and other human activities. Furthermore, the broader consequences of sublethal or localized effects for populations and ecosystems are seldom clear. The ramifications for biodiversity and living resource production of localized toxic effects or even the more extensive effects of nutrient pollution are difficult to quantify.

For the most part, the effects of pollution are reversible and respond to pollution abatement. The exception may be when marine mammals and birds are endangered by mass mortalities or reproductive failures resulting from toxic contaminants. Recovery can, however, be problematic and recovery times long, particularly with regard to persistent contaminants and permanent landscape changes that affect the delivery of pollutants from the watershed.

The nation's ocean and coastal ecosystems are being simultaneously affected by fishing activities (exploitation of target species, "bycatch," and effects of trawling), habitat modification from coastal development, and climate change, as well as by pollution. The relative importance of pollution as a threat to living resources depends on the region. Pollution is a fundamental concern in areas such as Boston Harbor, the northern Gulf of Mexico continental shelf, or the Chesapeake Bay. It is difficult to imagine environmental restoration and adequate resource management without controlling pollution. In other areas, pollution is much less a factor and habitat modification or fishing effects are far more important.

Most coastal ecosystems, in fact, experience multiple stresses. These stresses interact and, consequently, require integrated management solutions. Many coastal bays, for example, have been made less resilient to nutrient pollution because their oyster populations, which can filter out substantial amounts of organic matter, have been depleted. Furthermore, eutrophication will be influenced by the effects of climate change on freshwater runoff and water stratification (Justić et al.,1996; Najjar et al., 2000). And, overfishing of grazers makes coral reefs more susceptible to nutrient pollution (Lapointe, 1999). Multiple stresses can influence biodiversity on regional scales. For example, of 31 species of mammals, birds, and fish that have disappeared along the coast of the Netherlands over the past 2,000 years, 18 to 22 were as a result of overexploitation, 9 to 12 due to physical destruction of habitat, and 3 to 5 attributable to pollution (Wolff, 2000).

Priorities

Considerable strides have been made in reducing “conventional” forms of pollution over the last 30 years by implementation of the Clean Water Act and other federal, state, and local programs. Although further improvements are undoubtedly needed, technology-driven requirements and discharge permitting have been successful in greatly lowering the inputs of many contaminants into U.S. coastal waters. The dumping of sewage sludge and other wastes in the ocean was eliminated. The adverse effects of several manufactured chemicals (DDT, PCBs, and TBT) were uncovered and their use was discontinued or severely restricted.

This is not to say that protection of living marine resources from toxic wastes is no longer an important consideration for ocean policy. Decisions about managing legacy contamination and allowing the use of new chemicals still confront us. Atmospheric deposition and runoff from urban, suburban, and agricultural lands are now predominant pathways for toxic contaminants entering many coastal ecosystems. Abating these sources will require major commitments and innovative approaches.

We now realize that nutrients leaking from our land-based economy—from agriculture, transportation, power generation, and people—are having profound effects on coastal marine ecosystems over larger scales than imagined 30 years ago. The National Research Council (2000a) recommended that reducing nutrient pollution should be a national priority. Our society has just barely begun to accept and address this problem. Significant challenges lie ahead, particularly in ameliorating nitrogen pollution from diffuse sources.

"We now realize that nutrients leaking from our land-based economy —from agriculture, transportation, power generation, and people—are having profound effects on coastal marine ecosystems over larger scales than imagined 30 years ago."

Scales of Pollution Abatement

Meeting environmental quality objectives for the coastal ocean will require pollution abatement efforts at several scales. At the largest scale, managing anthropogenic alterations of the atmosphere and landscape well beyond the traditional “coastal zone” is required. Abating diffuse sources of pollution necessitates national laws and programs that harmonize agriculture, water resource, air quality, transportation, and land conservation policies with coastal environmental quality objectives. For example, the next reauthorization of the Farm Act should contribute to the reduction of nutrient pollution of coastal waters by targeting incentives, subsidies, and assistance while also

ensuring economically and socially viable agriculture for the nation.

At the programmatic scale, controlling diffuse sources is clearly the principal challenge for marine pollution abatement. The missing link for the next level of environmental advance is the design and implementation of sustained programs and institutions that address these diffuse sources and provide solutions that are acceptable to American society. Watershed approaches provide a framework but are constrained by weak authorities and the preeminence of traditional governance at state and local levels. The National Research Council (2000a) noted that effective control of multiple sources of nutrients and contaminants on watershed scales would require a mix of voluntary and mandatory approaches and hybrids of these two extremes. Incentives and disincentives included in statutes and management practices can be very important in promoting and shaping voluntary actions involving agriculture and land uses. At the same time, more effective compliance with mandates, such as those already applicable to urban stormwater runoff, should be required.

At the individual scale, many discrete gains may be realized. More demanding treatment standards than those generally applicable can be required where water quality is seriously impaired. Such case-specific requirements generally force technological innovations that are eventually applied more broadly.

Marine Ecosystem Management and Science

Effective ocean resource policies and management regimes must be integrated. Not only must they manage the fish, habitats, and pollution of the coastal ocean more compatibly, but they must also consider and coordinate with land-based activities. Existing regional programs that link activities in the watershed with coastal ecosystem management represent an important start, but much more remains to be accomplished to achieve full integration.

Recognizing inherent uncertainties, policies, and management regimes must also be precautionary and adaptive. As stated in the United Nations' Rio Declaration, the precautionary principle requires that: "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." Environmental decision-making in the United States has increasingly adopted a more precautionary approach—for example, in the testing of new pesticides and other chemicals before their release in the environment. While application of the precautionary principle may be straightforward in the screening of new chemicals or determining the suitability of dredged material for ocean disposal, it is harder when the ecosystems are already degraded or decisions concern which of many pollutant sources to reduce. Adaptive management involves periodic reevaluation and adjustment of the abatement approach based on careful observation of outcomes.

Integration, precaution, and adaptation in environmental policies and management all rely heavily on science. Scientific research and assessment must not only integrate across scientific disciplines but also address the interactions among the atmosphere, watersheds, and the ocean and relate pollution and other stresses to living marine resources and ecosystem services. The precautionary principle challenges science to quantify risk and determine the level of potential harm required to trigger its application. Adaptive management depends heavily on careful observations and comparison of outcomes to predictions.

Research, monitoring, and assessment relevant to marine pollution need improved strategic focus, organization, and commitment in order to fulfill these roles. The fundamental underpinnings of knowledge of complex environmental processes must be bolstered. The National Research Council (2000b) has identified grand challenges for environmental sciences, several of which are appropriate to marine pollution issues: biogeochemical cycles, biological diversity and ecosystem functioning, climate variability, hydrological forcing, land-use dynamics, and reinventing the use of materials.

Traditional environmental monitoring programs have emphasized relatively static parameters (e.g., contaminant concentrations in sediments or shellfish) rather than the dynamic parameters (e.g., primary production and dissolved oxygen) associated with the effects of nutrient pollution. Observing and understanding the effects of pollution should be an important objective of the sustained, integrated coastal ocean-observing system that is being developed for the nation (Nowlin and Malone, 1999). New sensor technologies, satellite measurements, and vast data storage and computational capabilities provide breakthrough opportunities to observe the environment on the appropriate space and time scales needed to address phenomena, such as eutrophication and harmful algal blooms, which occur over large areas but are highly variable in time.

Observations and research must be brought together in assessments that address key management questions and make useful predictions of probable outcomes. Predictions and observations must continually interact to support adaptive management. This will require new institutional arrangements and sustained commitments that support scientific integration and applied predictions.

VI. Conclusions

"Overenrichment by plant nutrients, particularly nitrogen, has emerged as the most pervasive pollution risk for living resources and biodiversity in coastal ocean ecosystems."

Significant accomplishments were realized during the last 30 years in reducing the pollution of U.S. ocean and coastal waters by improving the treatment of waste discharges, ceasing most ocean dumping, and eliminating or restricting the use of certain persistent toxicants. Substantial reductions were realized in the inputs of a number of potentially toxic contaminants and organic wastes. Pollutant inputs from regulated discharges will likely continue to decline in order to attain water-quality standards. However, except for the banned and restricted chemicals, inputs of pollutants from diffuse sources—including land runoff—were largely unabated or actually increased during the same 30 years. Diffuse sources now contribute more than direct discharges for many pollutants.

Although it is difficult to extrapolate effects observed in laboratory experiments, it is clear that toxic contaminants chronically affect marine organisms at least over limited, but widely distributed areas in U.S. coastal waters near heavily populated areas. Toxicants can also affect marine mammals and birds that concentrate organic compounds in fatty tissues, sometimes far from the pollution source.

Persistent and bioaccumulative toxicants remain in the ocean and coastal environment for long periods after their sources have been eliminated or substantially reduced. In many cases little can be done until the substances are gradually degraded or removed from the ecosystem. However, isolated sites have extremely high concentrations of toxicants in bottom sediments, from which they can be reintroduced to the ecosystem. Capping and removal options should be thoroughly evaluated by carefully weighing risks of alternative options.

Overenrichment by plant nutrients, particularly nitrogen, has emerged as the most pervasive pollution risk for living resources and biodiversity in coastal ocean ecosystems. Many of the nation’s coastal environments exhibit symptoms of overenrichment, including algal blooms (some of which may be toxic), loss of seagrasses and coral reefs, and serious oxygen depletion. Consequences include reduced production of valuable fisheries, threats to biodiversity on regional scales, diminished ecosystem services, and less resilient ecosystems.

Hard-to-control, diffuse sources—often from far inland—dominate nutrient inputs into most overenriched ecosystems. These sources grew dramatically in the last half of the 20th century as a result of increases in the use of chemical fertilizers, more intensive animal agriculture, and the combustion of fossil fuels that release nitrogen oxides into the air. Only recently has nutrient removal been incorporated in advanced treatment of point sources of wastes. New emission standards to meet air-quality objectives, if fully implemented, could reduce atmospheric deposition of nitrogen by 40 percent. Reduction of agricultural sources of nutrients has been more recalcitrant but it is feasible through improved practices and watershed restoration.

Reversing and controlling diffuse sources of pollution, including nutrients, requires an integrated approach on the scale of an entire drainage basin. The legal and institutional mechanisms available for reducing diffuse-source pollution have thus far been only modestly successful, but watershed management approaches are beginning to have an effect. A combination of voluntary and mandatory actions will be required, assisted by governmental incentives such as tax benefits and subsidies and disincentives. To be most effective, these incentives and disincentives should be targeted geographically. From the broadest policy perspective, effective ocean policy must extend well beyond the ocean and coastal zone to influence agricultural, energy, transportation, water resources, and land-use policies.

Science must play a key role in advancing marine ecosystem management that is integrated, precautionary, and adaptive. Sustained observations of changes related to pollution should be a key part of the nation’s integrated ocean-observing system. These results should be coupled with strategic research and models to improve predictions needed for adaptive ecosystem management.

Works Cited

Adler, R.W. 1995. Addressing barriers to watershed protection. *Environmental Law* 25:973–1106.

Alexander, R.B., R.A. Smith, and G.E. Schwarz. 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. *Nature* 403:758–761.

Anderson, S.D. 1999. Watershed management and nonpoint source pollution: the Massachusetts approach. *Boston College Environmental Affairs Law Review* 26:339–386.

Baker, J.E., ed. 1997. Atmospheric Deposition of Contaminants to the Great Lakes and Coastal Waters. Pensacola: SETAC Press.

Bell, P.R.F. 1992. Eutrophication and coral reefs—some examples in the Great Barrier Reef lagoon. *Water Research* 26:553–568.

Blankenship, K. 2000. Bay Program falling short of 40% goal to cut nutrients. *Bay Journal* 10(7): 1, 8–9.

Blus, L.J., R.G. Heath, C.D. Gish, A.A. Belisle, and R.M. Prouty. 1971. Eggshell thinning in the brown pelican: implication of DDE. *Bioscience* 21:1213–1215.

Boening, D.W. 2000. Ecological effects, transport, and fate of mercury: a general review. *Chemosphere* 40:1335–1351.

Boesch, D.F., and R.B. Brinsfield. 2000. Coastal eutrophication and agriculture: contributions and solutions, pp. 93–115. In *Biological Resource Management: Connecting Science and Policy* (eds. E. Balázs, E. Galante, J.M. Lynch, J.S. Schepers, J.P. Toutant, D. Werner, and P.A.T.J. Werry). Berlin: Springer.

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. In press. Chesapeake Bay eutrophication: scientific understanding, ecosystem restoration and challenges for agriculture. *Journal of Environmental Quality*.

Booth, D.B., and C.R. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association* 33:1077–1090.

Bricker, S.B. 1993. The history of Cu, Pb, and Zn inputs to Narragansett Bay, Rhode Island as recorded by salt marsh sediments. *Estuaries* 16:589–607.

Bricker, S.B., C.G. Clement, D.E. Pirhalla, S.P. Orlando, and D.F.G. Farrow. 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. National Oceanic and Atmospheric Administration, Silver Spring, Maryland.

Brown, B.E. 2000. The significance of pollution in eliciting the "bleaching" response in symbiotic cnidarians. *International Journal of Environment and Pollution* 13:392–415.

Bureau of Transportation Statistics. 2000. The Changing Face of Transportation. U.S. Department of Transportation, Washington, D.C. 26 December 2000. <http://www.bts.gov/transtu/cft/>.

Burroughs, R.H. 1988. Ocean dumping information and policy development in the USA. *Marine Policy* 12:96–104.

Caddy, J.F. 1993. Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. *Reviews in Fisheries Science* 1:57–95.

———. 2000. Marine catchment basin effects versus impacts of fisheries on semi-enclosed seas. *ICES Journal of Marine Science* 57:628–640.

Carls, M.G., S.D. Rice, and J.E. Hose. 1999. Low-level exposure during incubation causes malformations, genetic damage, and mortality in larval Pacific herring *(Clupea pallasi). Environmental Toxicology and Chemistry* 18:481–493.

Castro, M.S., C.T. Driscoll, T.E. Jordan, W.G. Reay, W.R. Boynton, S.P. Seitzinger, R.V. Styles, and J.E. Cable. 2000. Contribution of atmospheric deposition to the total nitrogen loads to thirty-four estuaries on the Atlantic and Gulf Coasts of the United States, pp. 77–106. In *An Assessment of Nitrogen Loads to U.S. Estuaries with an Atmospheric Perspective* (eds. R.M. Valigura, M.S. Castro, H. Greening, T. Meyers, H. Paerl, and R.E. Turner). American Geophysical Union, Washington, D.C.

CENR. 2000. Integrated Assessment of Hypoxia in the Northern Gulf of Mexico. National Science and Technology Council, Committee on Environment and Natural Resources, Washington, D.C.

CEQ. 1970. Ocean Dumping: A National Policy. Council on Environmental Quality, Washington, D.C.

Chesapeake Bay Program. 1999. Chesapeake Bay Basin Toxics Loading and Release Inventory. Chesapeake Bay Program Office, Annapolis, MD.

Chimka, C.T., J.N. Galloway, and B.J. Cosby. 1997. Ammonia and the Chesapeake Bay Airshed. Scientific and Technical Advisory Committee (Publication 97-1), Chesapeake Bay Program, Annapolis, MD.

Cochran, J.K., D.J. Hirschberg, J. Wang, and C. Dere. 1998. Atmospheric deposition of metals to coastal waters (Long Island Sound, New York U.S.A.): evidence from saltmarsh deposits. *Estuarine, Coastal and Shelf Science* 46:503–522.

Cooper, S.R. 1995. Chesapeake Bay watershed historical land use: impact on water quality and diatom communities. *Ecological Applications* 5:703–723.

Copeland, C. 2000. Water Quality: Implementing the Clean Water Act. Congressional Research Service (IB89102), Washington, D.C.

Corbett, J.J., and P. Fischbeck. 1997. Emissions from ships. *Science* 278:823–824.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253–260.

De Guise, S., A. Lagace, and P. Beland. 1994. True hermaphroditism in a St. Lawrence beluga whale *(Delphinapterus leucas). Journal of Wildlife Diseases* 30:287–290.

Diaz, R.J., and R. Rosenberg. 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanography and Marine Biology: An Annual Review* 33:245–303.

Duarte, C.M. 1995. Submerged aquatic vegetation in relation to different nutrient regimes. *Ophelia* 41:87–112.

EPA. 1991. Report to Congress on Ocean Dumping 1987–1990. EPA-503-9-91-009. U.S. Environmental Protection Agency, Washington, D.C.

———. 1997. Mercury Study Report to Congress. EPA-452-R-97-004. U.S. Environmental Protection Agency, Washington, D.C.

EPA and U.S.D.A. 1998. Clean Water Action Plan: Restoring and Protecting America's Waters. EPA-840-R-98-001. U.S. Environmental Protection Agency, Washington, D.C.

EPA. 1999. Polychlorinated Biphenyls (PCBs) Update: Impact on Fish Advisories. EPA-823-F-99-019. U.S. Environmental Protection Agency, Washington, D.C.

———. 2000a. The Quality of Our Nation's Water: A Summary of the National Water Quality Inventory: 1998 Report to Congress. EPA-841-S-00-001. U.S. Environmental Protection Agency, Washington, D.C.

———. 2000b. Cruise Ship White Paper. 22 Aug. 2000. U.S. Environmental Protection Agency, Washington, D.C. 2 Jan. 2000. <http://www.epa.gov/owow/oceans/cruise_ships/white_paper.pdf>.

———. 2000c. Deposition of Air Pollutants to the Great Waters: Third Report to Congress. EPA-453-R-00-005. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Forsberg, C. 1998. Which policies can stop large scale eutrophication? *Water Science and Technology* 37:193–200.

Fraser, M.P., and G.R. Cass. 1998. Detection of excess ammonia emissions from in-use vehicles and the implications for fine particle control. *Environmental Science and Technology* 32:1053–1057.

Frink, C.R., P.E. Waggoner, and J.H. Ausubel. 1999. Nitrogen fertilizer: retrospect and prospect. *Proceedings of the National Academy of Sciences, U.S.A.* 96:1175–1180.

Goldburg, R., and Triplett, T. 1997. Murky Waters: Environmental Effects of Aquaculture in the U.S. Environmental Defense Fund, Washington, D.C.

Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2000. Nitrogen flux and sources in the Mississippi River Basin. *The Science of the Total Environment* 248:75–86.

Hallegraeff, G.M. 1993. A review of harmful algal blooms and their apparent global increase. *Phycologia* 32:79–99.

Harvell, C.D., K. Kim, J.M. Burkholder, R.R. Colwell, P.R. Epstein, D.J. Grimes, E.E. Hofmann, E.K. Lipp, A.D.M.E. Osterhaus, R.M. Overstreet, J.W. Porter, G.W. Smith, and G.R. Vasta. 1999. Emerging marine diseases—climate links and anthropogenic factors. *Science* 285:1505–1510.

Healy, M.P. 1997. Still dirty after twenty-five years: water quality standard enforcement and the availability of citizen suits. *Ecology Law Quarterly* 24:393–460.

Hickey, J.J., and D.W. Anderson. 1968. Chlorinated hydrocarbons and eggshell changes in raptorial and fish-eating birds. *Science* 162:271–273.

Holmes, K.E. 2000. Effects of eutrophication on bioeroding sponge communities with the description of new West Indian sponges, *Cliona* spp. (Porifera: Hadromerida: Clionidae). *Invertebrate Biology* 119:125–138.

Hornberger, M.I., S.N. Luoma, A. van Geen, C. Fuller, and R. Anima. 1999. Historical trends of metals in the sediments of San Francisco Bay, California. *Marine Chemistry* 64:39–55.

Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J.A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch, and Z. Zhao-Liang. 1996. Regional nitrogen budgets and riverine nitrogen and phosphorus fluxes for the drainages to the North Atlantic Ocean: natural and human influences. *Biogeochemistry* 35:75–139.

Jansson, B.O., and K. Dahlberg. 1999. The environmental status of the Baltic Sea in the 1940s, today and in the future. *Ambio* 28:312–319.

Jaworski, N.A. 1990. Retrospective of the water quality issues of the upper Potomac estuary. *Aquatic Science* 3:11–40.

Johnson, K. 1999. The mythical giant: Clean Water Act Section 401 and nonpoint source pollution. *Environmental Law* 29:417–461.

Johnson, L.L., D. Misitano, S.Y. Sol, G.M. Nelson, B. French, G.M. Ylitalo, and T. Hom. 1998. Contaminant effects on ovarian development and spawning success in rock sole from Puget Sound, Washington. *Transactions of the American Fisheries Society* 127:375–392.

Justić, D., N.N. Rabalais, R.E. Turner, and Q. Dortch. 1995. Changes in nutrient structure of river-dominated coastal waters: stoichiometric nutrient balance and its consequences. *Estuarine, Coastal and Shelf Science* 40:339–356.

Justić, D., N.N. Rabalais, and R.E. Turner. 1996. Effects of climate change on hypoxia in coastal waters: a doubled CO_2 scenario for the northern Gulf of Mexico. *Limnology and Oceanography* 41:992–1003.

Kuehl, D.W., and R. Haebler. 1995. Organochlorine, organobromine, metal, and selenium residues in bottlenose dolphins *(Tursiops truncatus)* collected during an unusual mortality event in the Gulf of Mexico, 1990. *Archives of Environmental Contamination and Toxicology* 28:494–499.

Lapointe, B.E. 1999. Simultaneous top-down and bottom-up forces control microalgal blooms on coral reefs. *Limnology and Oceanography* 44:1586–1592.

Lauenstein, C.G., and K.D. Daskalakis. 1998. U.S. long-term coastal contaminant temporal trends determined from mollusk monitoring programs, 1965–1993. *Marine Pollution Bulletin* 37:6–13.

Lee, K. N. 1993. Compass and Gyroscope: Integrating Science and Politics for the Environment. Island Press, Washington, D.C.

Lewis, R.R. III, P.A. Clark, W.K. Fehring, H.S. Greening, R.O. Johansson, and R.T. Paul. 1998. The rehabilitation of the Tampa Bay Estuary, Florida, U.S.A., as an example of successful integrated coastal management. *Marine Pollution Bulletin* 37:468–473.

Long, E.R. 2000. Degraded sediment quality in U.S. estuaries: a review of magnitude and ecological implications. *Ecological Applications* 10:338–349.

Long Island Sound Study. 1998. Phase III Actions for Hypoxia Management. EPA-902-R-98-002. U.S. Environmental Protection Agency, Stony Brook, N.Y.

Looser, R., O. Froescheis, G.M. Cailliet, W.M. Jarman, and K. Ballschmiter. 2000. The deep-sea as a final global sink of semivolatile persistent organic pollutants? Part II: organochlorine pesticides in surface and deep-sea dwelling fish of the North and South Atlantic and the Monterey Bay Canyon (California). *Chemosphere* 40:661–670.

Mallin, M.A. 2000. Impacts of industrial animal production on rivers and estuaries. *American Scientist* 88:26–37.

Maritime Administration. 1994. The Dredging Process in the United States: An Action Plan for Improvement. U.S. Department of Transportation, Washington, D.C.

Mason, R.P., W.F. Fitzgerald, and F.M.M. Morel. 1994. The biogeochemical cycling of elemental mercury: anthropogenic influences. *Geochimica et Cosmochimica Acta* 58:3191–3198.

Mason, R.P., and W.F. Fitzgerald. 1996. Sources, sinks and biogeochemical cycling of mercury in the ocean, pp. 249–272. In *Global and Regional Mercury Cycles: Sources, Fluxes and Mass Balances* (eds. W. Baeyens et al.). NATO ARW Series. Amsterdam: Kluwer.

Mason, R.P., N.M. Lawson, and G.R. Sheu. 2000. Annual and seasonal trends in mercury deposition in Maryland. *Atmospheric Environment* 34:1691–1701.

Matthiessen, P., and P.E. Gibbs. 1998. Critical appraisal of the evidence for tributyltin-mediated endocrine disruption in molluscs. *Environmental Toxicology and Chemistry* 17:37–43.

McDowell, J.E., B.A. Lancaster, D.F. Leavitt, P. Rantamaki, and B. Ripley. 1999. The effects of lipophilic organic contaminants on reproductive physiology and disease processes in marine bivalve molluscs. *Limnology and Oceanography* 44:903–909.

Meade, R.H. 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. *Journal of Geology* 90:235–252.

Micheli, F. 1999. Eutrophication, fisheries, and consumer-resource dynamics in marine pelagic ecosystems. *Science* 285:1396–1398.

Milliman J.D. 1997. Blessed dams or damned dams? *Nature* 386: 325–326.

Mitsch, W.J., and J.G. Gosselink. 2000. Wetlands, Third Edition. New York: John Wiley and Sons, Inc.

Najjar R.G., H.A. Walker, P.J. Anderson, E.J. Barron, R.J. Bord, J.R. Gibson, V.S. Kennedy, C.G. Knight, J.P. Megonigal, R.E. O'Connor, C.D. Polsky, N.P. Psuty, B.A. Richards, L.G. Sorenson, E.M. Steele, and R.S. Swanson. 2000. The potential impacts of climate change on the mid-Atlantic coastal region. *Climate Research* 14:219–233.

National Research Council. 1985. Oil in the Sea: Inputs, Fates and Effects. National Academy Press, Washington, D.C.

———. 1993a. Managing Wastewater in Coastal Urban Areas. National Academy Press, Washington, D.C.

———. 1993b. Soil and Water Quality: An Agenda for Agriculture. National Academy Press, Washington, D.C.

———. 1995. Understanding Marine Biodiversity. National Academy Press, Washington D.C.

———. 1996. Stemming the Tide: Controlling Introductions of Nonindigenous Species by Ships' Ballast Water. National Academy Press, Washington D.C.

———. 1997. Contaminated Sediments in Ports and Waterways: Cleanup Strategies and Technologies. National Academy Press, Washington, D.C.

———. 1999a. From Monsoons to Microbes: Understanding the Ocean's Role in Human Health. National Academy Press, Washington, D.C.

———. 1999b. Hormonally Active Agents in the Environment. National Academy Press, Washington, D.C.

———. 1999c. New Strategies for America's Watersheds. National Academy Press, Washington, D.C.

———. 2000a. Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution. National Academy Press, Washington, D.C.

———. 2000b. Grand Challenges in Environmental Sciences. National Academy Press, Washington, D.C.

Nehring, S. 2000. Long-term changes in Prosobranchia (Gastropoda) abundances on the German North Sea coast: the role of the anti-fouling biocide tributyltin. *Journal of Sea Research* 43:151–165.

Nixon, S.W. 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. *Ophelia* 41:199–219.

Nixon, S.W., C.A. Oviatt, J. Frithsen, and B. Sullivan. 1986. Nutrients and the productivity of estuarine and coastal marine ecosystems. *Journal of the Limnological Society of South Africa* 12:43–71.

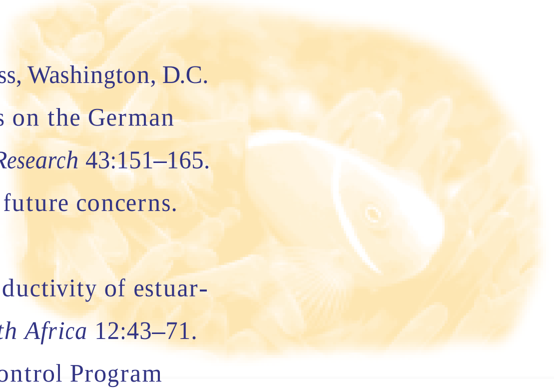
NOAA. 2000. Final Administrative Changes to the Coastal Nonpoint Pollution Control Program Guidance for Section 6217 of the Coastal Zone Act Reauthorization Amendments of 1990 (CZARA). National Oceanic and Atmospheric Administration, Silver Spring, MD.

Nowlin, W., and T. Malone. 1999. Toward a U.S. Plan for an Integrated, Sustained Ocean Observing System. Report to Congress. National Ocean Research Leadership Council, Washington, D.C.

Paerl, H.W., and D.R. Whitall. 1999. Anthropogenically-derived atmospheric nitrogen deposition, marine eutrophication and harmful algal bloom expansion: Is there a link? *Ambio* 28:307–311.

Pauly, D., V.S. Christensen, J. Dalsgaard, R. Froese, and F. Torres, Jr. 1998. Fishing down marine food webs. *Science* 279:860–863.

Rabalais, N.N., R.E. Turner, D. Justić, Q. Dortch, W.J. Wiseman, Jr., and B.K. Sen Gupta. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. *Estuaries* 19:386–407.



Raco-Rands, V. 1999. Characteristics of effluents from large municipal wastewater treatment facilities in 1996. In *Southern California Coastal Water Research Project Annual Report 1997–1998* (eds. S.B. Weisberg and D. Hallock). Westminster, CA.

Rex, A.C. 2000. The State of Boston Harbor 1997–1998: Beyond the Boston Harbor Project. ENQUAD 2000-05. Massachusetts Water Resources Authority, Boston.

Richardson, K., and J.P. Heilman. 1995. Primary production in the Kattegat: past and present. *Ophelia* 41:317–328.

Royal Society. 2000. Endocrine Disrupting Chemicals (EDCs). The Royal Society, London.

Ruhl, J.B. 2000. Farms, their environmental harms, and environmental law. *Ecology Law Quarterly* 27:263–349.

San Francisco Estuary Institute. 1996. Regional Monitoring Program for Trace Substances: 1995 Annual Report. San Francisco Estuary Institute, Richmond, CA.

Schiff, K.C., M.J. Allen, E.Y. Zeng, and S.M. Bay. 2000. Southern California Bight, pp. 385–404. In *Seas at the Millennium: An Environmental Evaluation* (ed. R.C. Sheppard). Oxford: Pergamon Press.

Scudlark, J.R., and T.M. Church. 1999. A Comprehensive Re-Evaluation of the Input of Atmospheric Nitrogen to the Rehoboth and Indian River Estuaries. Delaware Center for the Inland Bays, Lewes.

Smayda, T.J. 1997. What is a bloom? A commentary. *Limnology and Oceanography* 42:1132–1136.

Smith, S.V., W.J. Kimmerer, E.A. Laws, R.E. Brock, and T.W. Walsh. 1981. Kaneohe Bay sewage diversion experiment: perspectives on ecosystem responses to nutritional perturbation. *Pacific Science* 35:279–396.

Steding, D.J., C.E. Dunlap, and A.R. Flegal. 2000. New isotopic evidence for chronic lead contamination in the San Francisco Bay estuary system: implications for the persistence of past industrial lead emissions in the biosphere. *Proceedings of the National Academy of Sciences, U.S.A.* 97:11181–11186.

Swain, E.B., D.R. Engstrom, M.E. Brigham, T.A. Henning, and P.L. Brezonik. 1992. Increasing rates of atmospheric mercury deposition in midcontinental North America. *Science* 257:784–787.

U.S. Army Corps of Engineers. 1999. Ocean Disposal Database. 31 Oct. 2000. <http://www.wes.army.mil/>. Lkd. 1 Jan. 2001. <http://ered1.wes.army.mil/ODD/amount_by_year_of_all_the_districts.asp>.

U.S. Army Corps of Engineers (and other agencies). 1998. Long-Term Management Strategy (LTMS) for the Placement of Dredged Material in the San Francisco Bay Region. U.S. Army Corps of Engineers, San Francisco, CA.

Van Metre, P.C., B.J. Mahler, and E.T. Furlong. 2000. Urban sprawl leaves its PAH signature. *Environmental Science and Technology* 34:4064–4070.

Vitousek, P.M., J.D. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and D.G. Tilman. 1997. Human alteration of the global nitrogen cycle: sources and consequences. *Ecological Applications* 7:737–750.

Walker, J., Nelson, D., and V.P. Aneja. 2000. Trends in ammonium concentration in precipitation and atmospheric ammonia emissions at a coastal plain site in North Carolina, U.S.A. *Environmental Science and Technology* 34:3527–3534.

Wania, F., and D. Mackay. 1996. Tracking the distribution of persistent organic pollutants. *Environmental Science and Technology* 30:390A–396A.

Weber, P. 1993. Abandoned Seas: Reversing the Decline of the Oceans. Worldwatch Paper 116. Worldwatch Institute, Washington, D.C.

Weisberg, S.B., H.T. Wilson, P. Himchak, T. Baum, and R. Allen. 1996. Temporal trends in abundance of fish in the tidal Delaware River. *Estuaries* 19:723–729.

Whitaker, B. 2000. U.S. proposes partial cap of DDT site in the Pacific. *New York Times*, March 30, 2000, New York, NY.

Wolff, W.J. 2000. The south-eastern North Sea: losses of vertebrate fauna during the past 2000 years. *Biological Conservation* 95:209–217.

Wu, J., and Boyle, E.A. 1997. Lead in the western North Atlantic Ocean: completed response to leaded gasoline phaseout. *Geochimica et Cosmoschimica Acta* 61:3279–3283.

Yang, R.S.H. 1998. Some critical issues and concerns related to research advances on the toxicology of chemical mixtures. *Environmental Health Perspectives* 106 (Suppl. 4):1059–1063.

Zaitsev, Y.P. 1999. Eutrophication of the Black Sea and its major consequences, pp. 58–74. In *Black Sea Pollution Assessment* (eds. L.D. Mee and G. Topping). Black Sea Environmental Series Vol. 10. New York: UN Publications.

Zimmerman, R.J., and J.M. Nance. In press. Effects of hypoxia on the shrimp fishery of Louisiana and Texas. In *Coastal Hypoxia: Consequences for Living Resources and Ecosystems* (eds. N.N. Rabalais and R.E. Turner). American Geophysical Union, Washington, D.C.

Pew Oceans Commisssion

Connecting People and Science to Sustain Marine Life

The Pew Oceans Commission is an independent group of American leaders conducting a national dialogue on the policies needed to restore and protect living marine resources in U.S. waters. After reviewing the best scientific information available, the Commission will make its formal recommendations in a report to Congress and the nation in 2002.

Hon. Leon E. Panetta, Chair
Director, Panetta Institute for Public Policy

John Adams
President, Natural Resources Defense Council

Robert H. Campbell
Chairman and CEO (Retired), Sunoco, Inc.

Hon. Eileen Claussen
President and Chair of the Board
Strategies for the Global Environment

Hon. Carlotta Leon Guerrero
Guam Senate

Hon. Mike Hayden
President and CEO
American Sportfishing Association

Geoffrey Heal, Ph.D.
Garrett Professor of Public Policy and Corporate Responsibility, Graduate School of Business, Columbia University

Charles F. Kennel, Ph.D.
Director, Scripps Institution of Oceanography

Hon. Tony Knowles
Governor of Alaska

Jane Lubchenco, Ph.D.
Wayne and Gladys Valley Professor of Marine Biology
Oregon State University

Julie Packard
Executive Director, Monterey Bay Aquarium

Hon. Pietro Parravano
President, Pacific Coast Federation of Fishermen's Associations

Hon. Joseph P. Riley, Jr.
Mayor of Charleston, South Carolina

David Rockefeller, Jr.
Board of Directors, Rockefeller & Co., Inc.

Vice Admiral Roger T. Rufe, Jr.
U.S. Coast Guard (Retired)
President and CEO, Center for Marine Conservation

Kathryn D. Sullivan, Ph.D.
President and CEO, COSI Columbus

Marilyn Ware
Chairman of the Board
American Water Works Company, Inc.

Patten D. White
Executive Director
Maine Lobstermen's Association

Stephen M. Wolf
Chairman
U.S. Airways, Inc.

Pew Oceans Commission
2101 Wilson Boulevard, Suite 550
Arlington, Virginia 22201