CHAPTER 16

Impacts of Humans on the Oceans

CRITICAL CONCEPTS USED IN THIS CHAPTER

CC8 Residence Time
CC14 Photosynthesis, Light, and Nutrients
CC17 Species Diversity and Biodiversity
CC18 Toxicity

FIGURE 16-1. Adverse effects on the oceans that constitute pollution come in numerous ways, many of which do not involve the dumping or discharge of wastes that most people associate with the term pollution, but one species is the ultimate origin of all such adverse effects.

By far the most important human pollution of the oceans is the release of carbon dioxide and methane to the atmosphere. The adverse effects on the oceans that are predicted to occur as a result of carbon dioxide releases since the industrial revolution far transcend all other human impacts on the oceans combined. Massive disruption of marine **ecosystems** and likely numerous marine species extinctions are anticipated to result from the changing temperatures, current patterns, sea level rise, and especially from the deoxygenation and increased acidity of the oceans that has already occurred, or will occur. These already unavoidable adverse effects will become more severe if carbon dioxide releases are not drastically reduced. This issue is so important that it was discussed in some detail in Chapter 1 and referenced in many other chapters. This chapter explores the range of ways in which humans can, and do, adversely affect the oceans and examines the concept of pollution and of toxicity both of which are widely misunderstood. It then examines the wide range of human activities, such as sewage waste disposal, industrial waste discharges, and oil spills that have been the focus of most public concern and debate with regard to ocean pollution. Finally, the chapter examines the human activities that have caused significant harm, or pose a much larger threat to ocean ecosystems, most of which receive little or no public recognition or debate. These include, fishing, the introduction of nonindigenous species, habitat alteration, and finally the most important and greatest threats of climate change, deoxygenation and acidification caused by **anthropogenic** releases of carbon dioxide releases to the atmosphere and anthropogenic nutrient inputs to the oceans.

Chapter 2 reviewed the historical importance of the ocean and the growing use of ocean resources for fisheries; transportation; trade; extraction of offshore oil, gas, and other minerals; pharmaceuticals; energy; and recreational and aesthetic opportu-

nities. Each use potentially can or actually does have deleterious effects on ocean ecosystems and on the other uses of the ocean. Such deleterious effects are encompassed by the term **pollution**, which can be characterized as "the addition of substances to, or alteration of, the ocean ecosystem in a manner that is deleterious to the ocean ecosystem or its resources." This definition, or a similar one, is generally accepted by many national and international organizations that have responsibilities for managing and protecting the oceans and ocean resources. For example, the formal definition accepted by the premier world scientific body in this area, the United Nations Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), is as follows:

Pollution means the introduction by humans, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to maritime activities including fishing, impairment of quality for use of sea water and reduction of amenities.

Notice that, according to the generally accepted official definition, the term pollution includes not only the discharge of harmful wastes, but also activities such as **overfishing**, construction of structures, and other human activities that adversely affect ocean ecosystems by changing **currents**, distributions of dissolved substances or heat, or **sediment** transport patterns. The definition also includes adverse impacts of one ocean use on another, such as the degradation of recreational and aesthetic value caused by trash on ocean **beaches** or offshore oil rigs "spoiling" the ocean view. Ocean pollution also includes harmful effects on ocean ecosystems of the anthropogenic release of carbon dioxide and other greenhouse gases to the atmosphere, as these releases indirectly add carbon dioxide, a "waste" material and heat energy to the oceans. Thus, ocean pollution is a very broad term that includes any anthropogenic activity that causes directly or indirectly harm to ocean ecosystems or resources. Notice also that there must be harmful ("deleterious") effects before any activity can be considered pollution. By contrast, the popular definition of pollution continues to be restricted to the addition of substances (chemicals, materials, or organisms) to the **environment**, and the term often is misused to include any such contamination, whether "deleterious" or not.

POLLUTION VERSUS CONTAMINATION

All too often, any human activity that releases wastes or introduces particulate or dissolved substances to the ocean, either by accident or incidental to other activities, is mistakenly reported as "pollution." In many cases, however, such releases are benign or even beneficial to the ocean ecosystem and ocean resources. In such cases, the released material acts as a **contaminant** but no pollution has occurred. Only when the ocean ecosystem or ocean resources are damaged should the activity be called pollution. Hence, human activities may contaminate the oceans without polluting them.

One important note required here concerns the gross misuse of the term "pollutant." This term is applied to many substances that can have, and may have had, adverse effects on some ecosystem in which the concentration of the substances has been elevated by human activity to a level that has caused adverse effects and, therefore, pollution. There has been a popular use of the term "pollutant" to describe such substances, and then a popular trend toward calling the specific substance (for example, arsenic or cyanide) a pollutant. This misuse of the term has led many to believe that these substances are toxic and unacceptable at any concentration. However, this is never true. There is no substance known to humans that is always toxic at any concentration in any ecosystem. For example, arsenic is a natural element that is present in humans and other living organisms almost always at concentrations that cause no adverse effect (arsenic is benign), was once used extensively for medicinal purposes, and is the source of energy (by oxidation of arsenate to arsenite) for some species of bacteria in certain ecosystems. There are many compounds called cyanides, but "cyanide" usually refers only to hydrogen cyanide, which is toxic to humans at low concentrations, but which is naturally occurring in many ecosystems, produced by certain types of bacteria, and can provide the only source of nitrogen for other types of bacteria in certain ecosystems. In summary, no chemical always causes adverse effects (pollution) regardless of concentration in all ecosystems so there is no substance that can, or should be, always called a pollutant.

For many years, the oceans were considered so vast that human populations could safely discharge all their wastes there and carelessly exploit ocean resources such as fisheries and mineral deposits without causing adverse effects. In recent decades, the recognition that the oceans can be harmed by human exploitation and waste disposal has led to another viewpoint: that ocean ecosystems are so fragile that they must be protected from any human influence that may change them, and that no inputs of any contaminants can be permitted.

Just as the historical view of the oceans as limitless was wrong, this new view, although idealistic, is also incorrect. In some cases, the new view may have led to political decisions that, although they may possibly have reduced ocean pollution, also increased human health risks and terrestrial pollution. The oceans are naturally changeable, and humans have caused many changes in the oceans, just as we have in the terrestrial environment. If human civilization is to continue, further changes in both the terrestrial and ocean ecosystems are inevitable and necessary. We must learn to view the planet as a whole and recognize that we must use its resources wisely. We must accept contamination where necessary or desirable, and avoid pollution wherever possible, not only in the oceans but also on land and in the atmosphere.

Assimilative Capacity

The oceans receive millions of tonnes per year of many dissolved elements and organic substances from rivers, dust, and rain (**Chaps. 5 and 6**) and have done so since long before humans appeared on the Earth. These substances include many elements, such as copper, zinc, arsenic, and mercury, that are toxic to humans and other **species** if present at high enough concentration. The oceans also receive organic matter from soils, plants, and animal wastes, the composition of which is substantially the same as that of human fecal and urinary wastes.

The amounts of these substances introduced naturally must have varied substantially as **plate tectonics** modified and moved the continents and as the Earth's climate changed. Hence, ocean ecosystems can and have changed to accommodate a range of input rates of these substances. The maximum rate at which the oceans can accommodate such inputs without adverse effects is called the **assimilative capacity**. **Chapters 5 and 6** discussed some of the chemical and biological processes that remove substances from ocean waters to balance inputs and prevent concen-

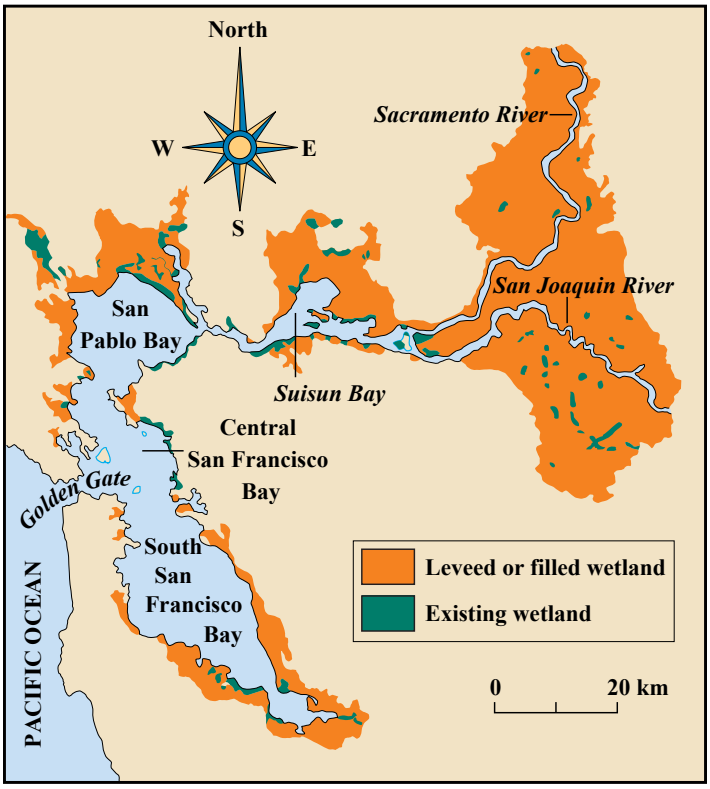


FIGURE 16-2. This map of San Francisco Bay and its delta shows the areas that were formerly wetland or part of the Bay but that have been filled or confined by levees in the past. The area of the Bay is now approximately one-half of what it was before 1850, and the area of remaining wetland is only a very small fraction of what it was then. Small areas that were previously filled have now been restored.

trations from rising continuously. The assimilative capacity is exceeded if the input rate increases so rapidly or by so much that removal processes are overwhelmed, and the concentration rises to a level that is toxic or has other adverse effects on the ecosystem.

Besides naturally occurring compounds, the oceans have an assimilative capacity, albeit sometimes small, for synthetic organic chemicals produced by human civilization. Although these compounds are new to the oceans, all (including plastics) are broken down by **decomposers** and chemical reactions into other compounds and eventually inorganic compounds. Some are broken down quickly, whereas others, including **DDT** (dichlorodiphenyltrichloroethane), **PCBs** (polychlorinated biphenyls), and many plastics are broken down very slowly.

Although assimilative capacity is a useful concept, it is very difficult to apply. Each element or substance has its own unique **residence time**, natural concentration, concentration at which it becomes toxic, variable toxicity to different species, and chemical and biological decomposition and removal processes. Each of these factors must be understood before the ocean's assimilative capacity for a single substance can be estimated. The oceans are not instantly and uniformly mixed. Consequently, the assimilative capacity can be exceeded for part of the oceans if inputs to a specific region exceed the rate at which they can be removed by chemical and biological processes and by mixing with the rest of the oceans. Hence, assimilative capacity and residence time are linked.

CC8 describes how residence times can be determined for individual substances. In a geographically distinct region, an increased input rate of a contaminating substance will cause the substance's concentration in the water (and thus, generally, in the sediments and biota of the region) to increase. The increase in concentration is greater if the residence time is longer. Thus, for example, organic material in the large volumes of sewage of a major city can far exceed the assimilative capacity of a river or bay if the water body has a relatively long residence time. The discharged organic material can be decomposed and deplete dissolved oxygen faster than the oxygen can be replaced by mixing with oxygenated ocean or river water or resupplied from the atmosphere. As a result, the water becomes **anoxic**, and toxic hydrogen sulfide is generated by bacterial action (**Chap. 12**). Parts of San Francisco Bay (**Fig. 16-2**), the New York Harbor, and many other **estuaries** developed chronic sewage-induced anoxia in the 1950s and 1960s.

The anoxia that affected many estuaries in the U.S. and elsewhere only several decades ago has now been alleviated in most instances. Today, all sewage is treated to remove most organic matter before being discharged as **effluent**. In addition, some, but not all, treated sewage has been diverted to **outfalls** discharging directly to coastal oceans, where the residence time is much shorter and the assimilative capacity much greater. Unfortunately, even the reduced-contaminant inputs exceed the assimilative capacity in some estuaries. Much of the oxygen demanding organic matter is now removed from all sewage in most industrialized nations, and this has led to the revival of many estuaries that formerly were severely degraded. However, treated sewage along with agricultural runoff are still largely responsible for areas of anoxia or **hypoxia**, commonly called dead zones, in a number of estuaries such as Chesapeake Bay. In many locations globally, treatment of sewage effluents has revived an estuary where relatively short residence times and restricted light penetration prevent rapid algal bloom formation only to create expanding seasonal or permanent anoxia and dead zones in the adjacent coastal ocean areas where residence time is much longer than in the estuary and turbidity is lower so algae can bloom freely

FIGURE 16-3. There are many sources of suspended sediment contaminant discharges to the oceans including some you might not expect. For example, sugar cane fields are often burned after harvest to clear the land for new planting. This practice increases erosion, and large amounts of suspended sediment are discharged in runoff. These fields are on the north shore of Hawaii. You can see the smoke from one of the fires and the plume of suspended sediment that spreads in the nearshore zone where there are reef-building coral formations that can be destroyed by excess sedimentation.

FIGURE 16-4. Coastal industries tend to reduce the aesthetic value of the shoreline. (a) The Moss Landing Power Plant, a very prominent structure located on the coast in the middle of Monterey Bay, California. (b) An oil refinery at Anacortes, Washington. (c) A marina at Antioch, California, constructed on a former wetland in the San Francisco Bay Delta.

as long as the nutrients (principally nitrogen), most of which remains in the treated sewage effluent during treatment, are available to sustain the growth. **Coastal zone** anoxia was discussed in more detail in **Chapter 13**.

A critical lesson here is that a discharge (nutrients in treated sewage effluents) in one location (the estuary) can produce contamination but no pollution, whereas a discharge of identical volume and composition in a region with a longer residence time (the adjacent coastal ocean) can produce a serious pollution problem. Hence, residence time and assimilative capacity are important parameters that must be considered when evaluating any activity that releases or may release contaminants. Because these parameters are location-specific, a release of a given type or amount of contaminant that has caused pollution problems in one location may not cause the same problems at other locations. Also, a release of a given type or amount of contaminant that has not caused pollution problems at one location may cause problems at another location.

ADVERSE EFFECTS OF HUMAN ACTIVITIES

Contamination and other human activities cause a variety of adverse effects, some of which are described here. In many instances, one activity can lead to more than one of the impacts discussed.

Interference with Photosynthesis and Respiration

Many contaminant inputs to the oceans contain large quantities of **suspended sediment** and light-absorbing organic matter. If retained in the water column, high concentrations of these materials block the penetration of sunlight and reduce the amount of light available for **photosynthesis** (**CC14**).

Human-caused discharges of suspended particles to the oceans primarily affect coastal regions (**Fig. 16-3**), where much of the ocean's **primary production** occurs. **Benthic algae**, both **microalgae** and **macroalgae**, are important primary producers in many coastal and estuarine areas. Excess suspended sediment reduces light penetration and, thus, primary production by benthic algae.

Adverse effects on primary production can be caused by discharges of large quantities of **nutrients**. Alterations in relative concentrations of nutrients can cause changes in phytoplankton species composition (**Chap. 13**). The result can have adverse effects on the food web if the newly advantaged phytoplankton species are unsuitable food for the zooplankton population.

Excessive nutrient discharges can increase primary productivity so dramatically that it exceeds the **grazing** capacity of consumers. In such cases, phytoplankton reproduce and grow rapidly in a **bloom** until the **limiting nutrient** is depleted. The bloom then collapses, and dead phytoplankton cells sink and decompose rapidly, removing some or all of the oxygen from the water. Reduction of oxygen concentration can adversely affect the **respiration** of fishes and **invertebrates**.

Oxygen depletion due to the presence of excessive nutrients or organic matter is called **eutrophication** and has long been a menace in lakes, rivers, and estuaries where nutrient inputs are large and residence times long. In many such areas, the nutrient and organic matter inputs are from sewage discharges. Sewage treatment has dramatically reduced eutrophication in U.S. lakes, rivers and estuaries since the early 1970s. However, nutrients remaining in the effluent after sewage treatment, when combined with other nutrient inputs, are now causing increased eutrophication problems (hypoxia and anoxia) in coastal oceans near estuaries. Hypoxia and anoxia that result from excessive nutrient inputs, and the increasing severity of these problems, were labeled in a 2000 report by the National Research Council of the National Academy of Sciences as the most pervasive and troubling pollution problem facing U.S. coastal waters.

Oxygen concentrations can also drop if photosynthesis is re-

duced. For example, increased concentrations of suspended sediment, copper, or other substances, such as herbicides, can inhibit photosynthesis and/or primary production without significantly affecting respiration in a marine ecosystem.

Human activities adversely affect oxygen concentrations in at least two special situations. First, when rivers are constrained within levees, the surface area is diminished but the river depth and currents increase. Often the **photic-zone** depth is naturally shallow and may be further reduced by higher **turbidity** caused by faster river currents that **resuspend** particulate matter. Because both the surface area and the depth of the photic zone are reduced, the total volume of the photic zone is smaller. Furthermore, the reduced surface area lowers the rate of oxygen resupply from the atmosphere.

In the second special case, oxygen concentrations are reduced because power plant, or other industrial, effluents have a higher-than-ambient temperature. Because oxygen has a lower **saturation solubility** at higher temperature, oxygen concentrations in the heated effluents are generally lower than ambient concentrations. This disparity is seldom an immediate problem, because the saturated oxygen concentration is sufficient to support respiration at all but the highest ocean water temperatures (above about 30°C). However, the low concentration of dissolved oxygen reduces the assimilative capacity for **oxygen-demanding** substances. Because tropical waters have high ambient temperatures and low ambient oxygen concentrations, oxygen depletion and sulfide production can be caused by smaller inputs of nutrients or organic matter in the tropics than in other **latitudes**. Hence, water bodies in tropical regions have a lower assimilative capacity for organic wastes than do water bodies with similar residence times at higher latitudes.

Habitat Alteration

Each species that lives in the oceans has its own requirements for the physical and chemical characteristics that constitute its **habitat** (Chaps. 14 and 15). Benthic species are particularly dependent on the nature of sediments in or on which they live. **Pelagic** species require, or prefer, certain ranges of temperature, **salinity**, turbidity, and current or wave regime. Many pelagic species depend on the benthic environment for food or shelter during part of their life cycle, whereas many others depend on the shallow-water environments of **mangrove** swamps, coastal **wetlands**, rivers, and estuaries during their juvenile phases.

Human activities have caused the destruction of vast areas of coastal wetlands and have caused adverse habitat alteration in other areas. For example, rivers have been dammed, preventing **anadromous** fishes, such as salmon, and **catadromous** fishes, such as eels, from migrating to the upper reaches of the rivers on which they depend. Levees, marinas, and ports have substantially altered current patterns, and thus suspended sediment transport routes, in many estuaries. Vast quantities of freshwater have been removed from many rivers, thus changing the salinity and other chemical characteristics of estuaries. Coastal structures have interfered with sand transport along many coasts. Large volumes of wastes have been discharged directly to the oceans or through rivers, and many parts of the seafloor have been damaged by dredging and dynamite blasting, and by anchors and fishing gear. All of these activities cause changes in **sedimentation rate**, sediment **grain size**, and sediment chemistry on the seafloor of affected regions. Sandy seafloor can be turned into mud and vice versa, and stable rocky or **reef** bottoms can be covered with sediment or broken up and **eroded** away.

Whenever marine habitat is altered, the species composition changes. Some species are disadvantaged and others benefit. Most often, the alteration causes at least a temporary reduction in species **diversity** (CC17) and dominance by species that are less sensitive to changing habitat. Opportunistic species that are not normally a major part of the biota commonly move into and dominate an environment when it has been altered by human activity, especially if the disturbance is ongoing, such as waste disposal or dredging. Although in some instances opportunistic species can enhance the **biomass** of the natural food web, more often they are less desirable or worthless in the natural food web.

Community Structure Alteration

The many species that make up a marine **community** depend on each other for food and in many other ways (Chaps. 14 and 15). The balance among species is determined by centuries or millennia of competitive and cooperative interaction that has enabled the community to reach a relatively stable state. If the balance is disturbed, the community structure can become unstable and change unpredictably.

The greatest direct human disturbances of community structure are caused by preferential exploitation of one or more species in a fishery or by the introduction, accidentally or otherwise, of **nonindigenous species** (discussed later in this chapter). Human activities may also introduce nonindigenous disease-causing organisms that affect some species important to the ecosystem. Other human influences, such as substrate alteration and introduction of potentially toxic substances, can also advantage or disadvantage certain species and cause community structure to be altered.

Marine communities are periodically subjected to habitat disturbances due to natural events, such as earthquakes and climate changes. Some additional human disturbance can be tolerated and accommodated by the ocean ecosystem. However, in some cases, anthropogenic disturbance may be more rapid or drastic than natural disturbances. Furthermore, human disturbances are often continuous or increase progressively, and their scale may be unprecedented in some coastal and estuarine areas.

Contamination of Food Resources

Aquatic species can obtain elements and compounds from food and directly from solution. Therefore, substances that are toxic to humans introduced in dissolved form or associated with organic particles can be assimilated by most marine organisms and passed through the food web. Many marine species are tolerant of relatively high concentrations of potentially toxic elements or compounds in their environment or food, probably because their body surface and respiratory tissue are continuously exposed to seawater. Rather than building defenses against the absorption of potentially toxic substances from their environment, many marine species simply take up such compounds and store them in some organ where they cannot interfere with essential **biochemical** processes. This method of detoxification has limits, but it enables many marine species to tolerate high concentrations of some substances.

Fish and **shellfish** with high concentrations of stored potentially toxic substances may suffer no adverse effects but may still pose a significant risk to human health. Shellfish, such as oysters, are particularly adept at concentrating trace metals, and many synthetic organic compounds, such as DDT and PCBs which are both concentrated in fatty tissues of most marine animals.

High concentrations of metals and synthetic organic compounds have been found in the biota from many locations where human activities release such contaminants. In these locations, the fishery or shellfishery is closed, or people are advised to eat only limited amounts of seafood or a specific seafood species. Thus, the value of the fishery resource is diminished or lost. Fortunately, in only one recorded instance have people died from ingesting seafood contaminated with industrial toxic substances discharged into the oceans. That incident, in Minamata, Japan, is discussed later in this chapter.

Contamination of fish and especially shellfish with microorganisms that are human **pathogens** is a serious problem. Because some seafood is eaten raw or only lightly cooked, any microorganisms present will be passed on to the consumer. Seafood may be contaminated during handling and processing, although refrigeration and hygienic food-handling techniques have greatly reduced this problem in most developed countries. Most microbiological contamination of seafood now comes from the harvested waters. The problem areas are generally contaminated by discharges of raw or treated sewage or by animal feces carried in street and land runoff. The contamination is concentrated in estuaries and the coastal zone because human pathogens are progressively diluted and destroyed by marine microbes as they are transported to the open oceans. Unfortunately, shellfish beds are located mostly in coastal and estuarine zones.

Some pathogen-contaminated shellfish can be collected and cleansed by being kept in pathogen-free, constantly running and renewed seawater, but this procedure is expensive and requires a source of reliably pathogen-free seawater. Consequently, the only practicable way to prevent the spread of disease by contaminated shellfish is to prohibit harvesting in contaminated areas. At present, many potentially valuable shellfishing areas of the coastal oceans and estuaries in the contiguous U.S. are closed to shellfishing for at least part of the year. The total area closed is increasing, despite immense expenditures for sewage treatment and control of other contaminant sources since 1972, when the U.S. passed the Clean Water Act requiring secondary treatment of almost all sewage.

Toxin-producing phytoplankton blooms are also a growing contamination problem. These blooms, the toxins they produce, and their effect on marine ecosystems and seafood values are discussed in **Chapter 13**.

Beach Closures and Aesthetic Losses

Many people look to the coastal oceans as places of aesthetic beauty where they can renew their contact with the natural world through various recreational activities. As a result, one of the largest industries on the planet has developed around coastal recreation. However, the value of the coast for such activities is compromised and diminished in many locations by the presence of human structures that mar the natural beauty (**Fig. 16-4**) and interfere with natural processes.

Many coasts that otherwise would be areas of high recreational value are sites of human industrial and residential developments that bar the public from reaching the **shore**. Such developments often cause major changes in the coastal form and function through direct modifications of the **shoreline**, such as **bulkheads**, piers, and groins, and through alteration of the coastal current, wave, and sediment transport patterns (**Chapter 11**). In addition, vast areas of biologically important coastal wetlands have been drained and filled to accommodate development (**Fig. 16-2**). Today there is a growing realization that many of these developments were ill-planned. Public opinion now favors protection of the coast from unreasonable degradation by development, although the legal system lags behind this imperative.

Outfalls discharge treated sewage, industrial waste, and storm-water runoff to rivers, estuaries, and oceans. Rivers also receive various materials that have been carelessly or deliberately dumped by humans. Vessels often discharge wastes directly into the ocean. Many beaches are periodically closed to swimming because the water is contaminated with pathogens from improperly treated sewage. In addition, floating debris mars beaches and, in extreme cases, leads to the temporary closure of beaches for recreational purposes. For example, medical wastes, including syringes, apparently dumped in nearby rivers or from vessels, have periodically washed up on New York and New Jersey beaches, prompting closure of the beaches for fear that the materials could carry pathogens, including the HIV **virus**.

TOXICITY

Toxic substances are substances that have adverse effects on organisms, including humans. The term toxic chemical is now among the most emotion-evoking in our society. In fact, there is a widespread belief, fostered by the media and many environmental interest groups, that the release of any quantity of toxic chemicals to the environment, particularly the oceans, is harmful and must be stopped. This belief is unfounded (**CC18**). Many chemicals that are toxic at high concentrations are naturally occurring elements or compounds that have been present in the oceans throughout geological time. Some additional quantities, in many cases substantial quantities, of these substances and even synthetic chemicals that do not occur naturally can be safely accommodated by ocean ecosystems. However, if they are to cause no harm, wastes must be disposed of in ways that ensure that the ocean's assimilative capacity is not exceeded either globally or locally. Marine pollution problems occur when chemical discharges exceed the assimilative capacity and cause adverse effects, including lethal or non-lethal toxicity to species within the ocean ecosystem. Therefore, determining this capacity for each local region into which toxic substances are discharged is an important scientific task.

A second widespread belief is that the ultimate solution to contamination by toxic chemicals is to recycle everything. Recycling is a highly desirable and rapidly growing practice that continues to reduce quantities of potentially toxic chemicals released to the environment. However, recycling can never be 100% effective. Chemicals that can be toxic at high concentrations are present in small quantities in almost every natural and synthetic product in our society, including human waste excretions. For many of society's waste products, the energy costs and associated adverse environmental effects of recycling and removal of traces of potentially toxic chemicals may far outweigh the environmental costs of properly managed disposal of the waste. In addition, storing all toxic chemical–containing wastes in "secure" landfills is not feasible. In most instances, using valuable land to dispose of large-volume wastes that have low concentrations of toxic chemicals is inappropriate. Perhaps more importantly, no landfill can ever be secure on a geological timescale. Wastes containing high levels of long-lived potentially toxic substances that are buried in landfills will eventually release these substances to freshwater and **groundwater** and from there to the oceans. The

Earth's freshwater resources are severely limited, and any contamination of the freshwater poses a threat to human health and terrestrial ecosystems. Consequently, many environmental scientists believe that properly managed ocean disposal of wastes may be the environmentally preferable management option for wastes that cannot be efficiently recycled and that have low concentrations of potentially toxic chemicals.

The fate and effects of chemicals in the oceans are determined by how they are transported by currents, how they are removed and incorporated in sediments, and how they are taken up by the marine biota. Several chapters in this text describe the movements of ocean water and suspended sediment and the processes of marine **sedimentation** that determine the distribution and ultimate fate of dissolved and particulate constituents in the oceans.

Effects of Toxic Substances on Marine Organisms

CC18 describes the general principles that determine the toxicity of substances to living organisms. The essential point is that most substances are toxic to a specific organism only when their concentration in food or in solution in the surrounding water exceeds a certain level, above which, the concentration of the chemical within the organism is high enough to interfere with one or more biochemical processes critical to the organism's life cycle. For all potentially toxic chemicals, there is a concentration below which the chemical has no adverse effects.

The only exception to this rule may be for compounds that are **carcinogens** (cancer-causing), **mutagens** (causing **genetic** changes in the offspring by altering the parents' **DNA**), or **teratogens** (causing abnormal development of the **embryo**). There are conflicting views about whether a threshold concentration exists for such compounds. If there is no threshold concentration, any concentration of the compound will increase the incidence of disease. However, below a certain concentration, the number of individuals affected by a carcinogenic, mutagenic, or teratogenic chemical will be far smaller than the number similarly affected by naturally occurring compounds and natural **radioactivity**, which also have such effects. Hence, even for these compounds, there is a concentration below which they have no significant adverse effects.

Evaluating Toxicity

Assessing the toxicity of substances to marine organisms is very difficult. Two general approaches are used. First, the distribution of species in an ocean region affected by inputs of that substance can be compared with the distribution in similar but unaffected regions or in the affected region before the anthropogenic inputs occurred. Second, **bioassays** can be performed in the laboratory to test the responses of organisms to various concentrations of the chemical (**CC18**). The laboratory results must be extrapolated to what might occur in the environment. Both approaches are difficult and prone to errors and uncertainties.

The field approach to toxicity evaluation requires a very detailed survey of the affected ecosystem and of control sites. Researchers must characterize the population levels and health of many species to be certain that the most susceptible species are included. Moreover, changes observed in the ecosystem may be caused by natural factors, such as climate variations. Hence, even if a significant difference in the ecosystem is observed between test and control sites, researchers usually cannot eliminate the possibility that it is natural and unrelated to contaminant toxicity. In addition, most contaminated locations receive inputs that contain a variety of toxic chemicals, all of which vary in concentration with time. Assessing which contaminant might be responsible for an observed change is difficult.

At present, we do not have a detailed understanding of the effects of toxic substances in the oceans, and we cannot predict with certainty the consequences of specific concentrations. Management of ocean uses that involve the release of toxic chemicals to the marine environment is therefore difficult and controversial. However, our understanding of the effects of toxic chemicals in terrestrial, freshwater, and groundwater ecosystems, and on human health, is not significantly better than our understanding of their effects in the marine environment. There is general agreement that we must exercise caution and, where practical, limit the release of potentially toxic chemicals to the environment. Nevertheless, wastes containing low concentrations of potentially toxic chemicals will always require disposal. If properly managed, ocean disposal of these wastes may be both safe and environmentally preferable to other disposal methods.

Bioaccumulation and Biomagnification

Two processes cause concentrations of substances that are potentially toxic to humans in marine organisms to become elevated in relation to concentrations in their food or environment (**CC18**): **bioaccumulation** and **biomagnification**.

Uptake and excretion of toxic substances by marine organisms are typically complex processes that involve transfers of the toxic substance among several different tissues of the organism, as well as to and from the organism's food and the surrounding water. Hence, some toxic substances may be taken up quickly when the environmental concentration increases, but released much more slowly when the environmental concentration decreases. The complexity of these bioaccumulation equilibria generally increases as the organism becomes more complex.

Higher order animals tend to store toxic substances in tissues where they are least harmful. Toxic substances are excreted only very slowly from these tissues after the exposure is reduced. In some cases, the loss is so slow that the concentration of the toxic substance tends to increase progressively during the individual organism's lifetime. The cumulative buildup of metals, such as lead, mercury, and arsenic, in human beings during their lifetime is an example. In such situations, short-term laboratory bioassay tests cannot accurately reflect the effects of long-term exposure to toxic substances or wastes.

Biomagnification is a special situation in which substances that are taken up by an organism from food or water are stored in tissues and there is no route by which these stored substances can be released. Biomagnified substances not only accumulate throughout an organism's lifetime but are transferred up the food chain so that the substance accumulates to higher concentrations with each step in the chain.

Trace metals are not biomagnified in marine food webs, except in a few instances when the metal is organically combined, such as in the methylated form of mercury. Biomagnification in ocean food webs appears to be limited to compounds that are highly soluble in fatty tissues and have relatively low solubility in water. These mainly include synthetic organic compounds, of which DDT and PCBs, and perhaps a few synthetic or naturally produced metal-organic compounds, such as methylmercury and tributyltin, are the primary ones.

Biomagnification of DDT and its decomposition products was responsible for the decline of pelican, sea lion, and elephant

seal populations off California and throughout the eastern Pacific Ocean during the 1950s and 1960s. Almost all uses of DDT were banned in the U.S. in 1971. Since then, each of the affected species has recovered steadily in the eastern North Pacific Ocean. However, DDT continues to be used elsewhere in the world, particularly in tropical regions. Both DDT and its toxic but longer-lasting decomposition products are still found at high concentrations in marine species at higher **trophic levels** in all parts of the oceans.

Synthetic and Naturally Occurring Toxins

Two distinct classes of toxic substances are released to the marine environment by human activities: naturally occurring substances, including trace metals (e.g., copper, lead, cadmium) and petroleum hydrocarbons; and synthetic chemicals produced only by human industries (e.g., DDT and PCBs). These two classes should be viewed differently.

Marine organisms are adapted to generally low but variable concentrations of natural toxic substances in their environment. For example, lead and other toxic metals are either safely stored within marine organisms' tissues where they do not affect critical biochemical processes or safely excreted back to the environment. Petroleum hydrocarbons are metabolized to harmless substances by many fish species and used as food by many marine decomposers. Adverse effects occur only when these natural detoxification processes are overwhelmed by high concentrations of such compounds. This is fortunate, because total elimination of the releases of such compounds by all human activities is impossible.

Synthetic chemicals, such as DDT and PCBs, are not present naturally, and marine organisms may not have mechanisms to detoxify them. Consequently, these compounds have more unpredictable fates and effects in the marine environment. If they are persistent and not easily broken down by the chemical processes or metabolic processes of marine organisms, they tend to accumulate, persist, and cause adverse effects. Unlike contaminants that occur naturally, a synthetic chemical can be eliminated completely from our society and therefore from any further introduction to the environment. Alternate synthetic chemicals have now been designed and developed that adequately fulfill the purposes for which DDT and PCBs were intended but that, in contrast, are readily and rapidly decomposed in the environment. Unfortunately, developing, testing, and manufacturing new, effective, and rapidly biodegradable chemicals is very costly. The widespread adoption of such expensive replacement products is impeded primarily by economic factors, especially in poorer nations.

WASTE DISPOSAL

For centuries, the oceans were viewed as a limitless sink for waste disposal. Consequently, during the industrial era, the oceans were used to dispose of sewage, dredged materials, construction dirt and debris, trash and garbage, chemical wastes, radioactive wastes, fish-processing wastes, used machinery and boats, and almost anything else that people needed to discard. Wastes have been dumped from vessels or discharged through outfalls into rivers, estuaries, and the ocean. Since the 1970s, indiscriminate use of the oceans for waste disposal has been recognized to cause adverse environmental impacts, some of them severe. As a result, ocean waste disposal is now viewed in the U.S. and elsewhere as being universally unacceptable. With the exception of dredged material, ocean dumping from vessels is now illegal in the U.S. and most other developed nations. In addition, stringent rules are in place that require sewage and industrial wastes to be treated before they are discharged through outfalls.

Contrary to popular belief, many marine scientists believe that properly managed disposal of certain wastes in the oceans is not only acceptable, but may be environmentally preferable to any possible alternative disposal or recycling technology for these wastes. Properly managed disposal of certain organic and nutrient-containing wastes, such as sewage and fish-processing wastes, might even have beneficial effects if done appropriately. However, because all ocean disposal is considered unacceptable by the media and the public, little or no research is being done to define how, where, and what types of wastes can and should be safely disposed of in the oceans. This situation may eventually prove detrimental to the global environment. Many wastes, particularly wastes containing toxic trace metals, might be safely dispersed in and assimilated by the oceans and/or removed by natural processes to ocean sediments (where they reenter the global biogeochemical cycle at a point where they are removed from contact with the biosphere for millennia), but instead they are buried in "secure" landfills from which they will eventually

FIGURE 16-5. Oil spills provide spectacular images that ensure media coverage. (a) The *Exxon Valdez* tanker 48 h after it ran aground on Bligh Reef in Prince William Sound, Alaska, in 1989. In this photograph, the tanker is seen still leaking some oil, and it is surrounded by a boom that has been placed on the water surface in an attempt to contain this oil so that it can be collected. (b) A rescuer tries to capture an oiled Pelican after the 2010 *Deepwater Horizon* spill in the Gulf of Mexico. Rarely do heavily oiled birds survive even when cleaned up.

FIGURE 16-6. Major oil spills from the offshore oil industry are rare but dramatic events such as the *Deepwater Horizon* rig which is shown burning before it sank in the Gulf of Mexico, April 2010.

be released into the ground, groundwater, and then rivers and oceans.

OCEAN POLLUTION ISSUES

Petroleum

If asked to identify the sources of serious pollution in the oceans, most people would name oil spills at, or near, the top of their list. This is not surprising, since oil spills, unlike any other form of ocean pollution, provide spectacular images and video of leaking tankers (**Fig. 16-5a**), oiled marine animals and birds being rescued or dead on a beach (**Fig. 16-5b**), and towering flames and smoke from burning oil rigs (**Fig. 16-6**). As a result, media coverage of oil spills is always extensive, and since bad news sells better than good news, the media tends to emphasize and often exaggerate the extent of the environmental harm. In contrast, most other ocean pollution is almost impossible to photograph or video so gets little or no media attention. The net result of this is that the public perception is that oil spills are the most serious form of ocean pollution and that huge sums of money must be spent to monitor the impacts of each spill and to provide absolute assurance that spills "never occur again." Many marine oil spills have been extensively studied over more than the past half century and the findings of such studies support a different conclusion. While spill prevention is important and oil spills do have adverse impacts on the area in which they occur, the adverse effects are geographically limited and the affected marine ecosystems recover to a natural state (not to the same state as before since ecosystems are naturally always changing and a previous state can never be restored exactly) within a few years.

Oil spills are discussed in more detail in **Online Box 16B1**, but some of the more important findings are summarized here.

1. Oil is a natural substance that is consumed by microbial decomposers.
2. Oil spills have short-term adverse effects in the spill area including, deaths of birds and some marine animals due to oiled fur or feathers, oiled beaches, and disruption of plankton communities. Long-term effects are uncertain but may include some reduction in reproductive success of some marine species.
3. Ecosystems subject to spilled oil recover to a natural state within years in most areas to a decade or more in cold regions.
4. The use of dispersants or aggressive cleanup techniques such as hot water washing of rocky coastline or beaches generally leads to greater harm to the ecosystem than simply skimming off as much oil as can be done easily and allowing the microbial community to remove the remainder (adding nutrients to aid these microbial organisms may be appropriate in some cases).
5. Efforts to rescue and clean oiled marine animals and birds are often very expensive but result in very low survival rates for the cleaned animals.
6. Measures taken over the past several decades to minimize oil spills from tanker accidents and other accidental spills have been largely successful in reducing the frequency of large spills.
7. Chronic inputs of petroleum products from dispersed sources such as runoff from highways are still large and may have chronic adverse effects in some locations, especially rivers and estuaries where such inputs are large.

Sewage

Some human waste has been disposed in oceans, estuaries, and rivers for millennia. However, once sewers systems were introduced, they acted as a public health tool to ensure that human wastes were carried easily and efficiently for disposal in nearby bodies of water. Sewers are historically so important that human wastes are now called sewage. Sewage is a combination of liquid and solid natural materials that was disposed of in rivers, estuaries and oceans for centuries after sewers were introduced, generally without causing adverse effects on the discharge ecosystem. Most cities were, and still are, located next to or near rivers, estuaries or a coastline for reasons that included the availability of these bodies of water into which sewage could be discharged. As the human population grew and cities became ever larger, the quantities of sewage discharged increased as did the concentrations of sewage waste in bodies of water near these cities. By the mid 20th century, many rivers and estuaries worldwide were anoxic. This anoxia was caused by microbial decomposition of sewage organic matter that consumed oxygen faster than it could be replaced from the atmosphere. The ecosystems of many rivers, estuaries, and even some coastal ocean areas were severely damaged and waterside locations in many areas became undesirable places to live or work because of the smell of sulfide and partially decomposed organic matter. This was one of the primary driving reasons for the environmental revolution of the 1960s and 1970s.

The problems caused by sewage waste discharges prior to the 1970s were primarily due to the high organic matter loading of untreated sewage. Sewage treatment was developed and designed to address this problem by collecting sewage wastes in treatment plants where the larger particle solids could be filtered or precipitated out (primary treatment) and then treated with bacteria to decompose the organic matter that remains after primary treatment (secondary treatment). Both steps generate sludge (mostly particulate solids with enough water to allow them to flow as a thick slurry). Secondary treatment of sewage is now required in the U.S. and in most nations and large cities, and has proved to be effective in alleviating the anoxia problems. Most river, estuary and ocean ecosystems that were damaged by overloading of

organic matter from sewage have now recovered.

Despite the success of sewage treatment, several issues still remain because secondary sewage treatment is not designed to remove trace metals, many soluble organic compounds, human pathogens, or dissolved inorganic nitrogen and phosphorus, although it does partially remove most of these. In most areas, sewage entering sewage treatment plants is a mixture of: human waste water, water used for washing and cleaning that often contains potentially toxic chemicals, wastewaters from some industries, and in some areas storm drain runoff. These are all mixed in one waste stream. In the U.S. and many other nations, industrial pretreatment programs have been highly effective in drastically reducing inputs to sewage of trace metals and potentially toxic organic compounds from industry before they reach the treatment plant. Street cleaning and other measures have somewhat reduced storm runoff of metals and potentially toxic organics. Efforts to improve the removal of remaining non industrial continue to make slow progress.

Most pathogens in sewage are killed quickly in estuaries and ocean water but extensive monitoring programs are still required to assure that pathogen concentrations on swimming beaches are safe. Beach closures due to sewage discharges still occur infrequently when treatment plants have technical problems or when those sewage treatment plants that must treat storm water runoff combined with the sewage waste stream are overwhelmed by large rainfalls.

Sewage treatment has been perhaps the greatest success story in environmental management since the environmental movement began. Nevertheless, some issues remain, and a new one is increasingly becoming apparent. This issue is the nutrient loading due to treated sewage wastes. Recall, that secondary treatment was not designed to reduce the concentrations of nutrients like nitrogen and phosphorus and does not do so effectively. Recall also from earlier chapters that anoxia and dead zones driven by discharges of nutrients from rivers are a major and growing problem worldwide (**Chaps. 1, 12, and 13**). Treated sewage discharges to rivers are a major contributor to the nutrient inputs that cause coastal dead zones and likely also cause an increase in total primary production in the surface oceans that contributes to the problem of deoxygenation of the deep oceans discussed in **Chapter 1** and later in this chapter. Tertiary treatment technologies do exist to reduce nutrient concentrations in sewage but they are not widely used. These tertiary treatment technologies are costly to perform and require large capital expenditures to upgrade and expand existing sewage treatment plants.

A more detailed discussion of sewage and sewage treatment can be found in **Online Box 16B2**.

Urban and Agricultural Runoff

Many chemicals are used in urban and agricultural communities. Fertilizers and pesticides are applied in large quantities to fields and gardens. Oil and rubber dust (containing toxic contaminants such as cadmium) are left on road surfaces by vehicles. Hydrocarbons and other chemicals are released from road-paving and other building materials. Particulates injected to the atmosphere from the burning of fossil fuels settle everywhere. Paints, solvents, acids, and other chemicals are spilled or released in many different ways, and toxic chemicals are still deliberately dumped to avoid costs of proper disposal. There are also many other ways for toxic contaminants and nutrients to be deposited on the land.

When it rains, contaminants are either absorbed into the soil or washed off into storm drains, streams, rivers, and eventually estuaries and the ocean. Many contaminants are carried by runoff in dissolved form, but most are carried on small organic-rich particles. These particles are carried by streams and rivers to estuaries and coastal ocean, where they can become trapped in the estuarine circulation and sediments (**Chap. 13**). Contaminants from urban and agricultural runoff reach estuaries through numerous drainage channels spread throughout the watershed. Consequently, their sources are often referred to as nonpoint sources. Nonpoint source inputs are highly variable. Such inputs are greatest during the first few hours of a rainfall, especially if it follows a prolonged dry period. Thus, contaminants that are carried into the estuarine and marine environment generally are diluted by large quantities of freshwater. These factors make the identification and control of nonpoint sources of contaminants extremely difficult and make the cost of possible treatment in most instances prohibitively high.

Urban and agricultural runoff contributes a major proportion of the nutrients and contaminants that enter many estuaries and coastal embayments. Substantial efforts have been made to control nonpoint sources. However, success has been limited, and nonpoint sources are still much greater than industrial and sewage inputs in most estuaries. Consequently, where such substances cause pollution problems, further controls on industrial and sewage inputs will have only a minor effect. The difficult task of controlling nonpoint source inputs must be addressed successfully if estuarine and coastal ecosystems are to be fully protected and restored.

Pollution problems caused by urban and agricultural runoff are many and varied. Two examples illustrate the complexity of such problems. First, in Chesapeake Bay, nutrient-induced eutrophication has led to widespread, persistent anoxia. Although sewage discharges contribute some nutrients, the predominant sources are fertilizer and animal waste in runoff from surrounding agricultural land, as well as atmospheric inputs. Extensive efforts have been made to reduce these nonpoint source inputs—for example, by reducing fertilizer use and avoiding its application near streams. These efforts have resulted in some improvement, but the problem remains a difficult one.

The second example is the "dead zone," of the nearshore **continental shelf** of the Gulf of Mexico in which the bottom waters are seasonally hypoxic (**Chap 13**). The Gulf dead zone is located in the middle of one of the most important commercial and recreational fisheries in the U.S. The Mississippi River basin drains about 41% of the Lower 48 states of the U.S.—a total of over 3.2 million km^2. The drainage basin encompasses all or part of 30 states, a population of about 70 million people, and extensive agriculture. The Mississippi River discharge contains a high nutrient level, some of which is natural but much of which comes from runoff of fertilizers applied to farmlands and from treated sewage. In the last four decades of the twentieth century, the discharge of nitrogen by the Mississippi River basin tripled. It is this excess nutrient load that is believed to have created the dead zone, which was first documented in 1972. Efforts to reduce the nutrient loads of the Mississippi River are under way, but, as in the Chesapeake Bay region, these efforts are difficult and will take many years if the dead zone is to be eliminated.

Industrial Effluents

Most industries produce solid or liquid wastes that dif-

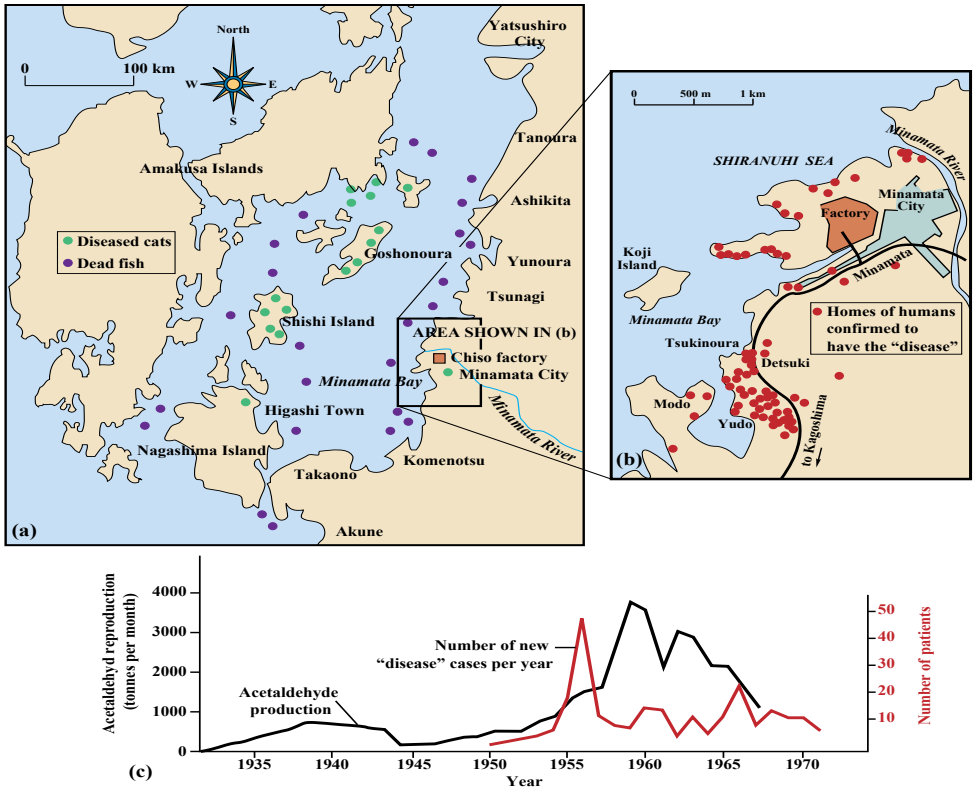


FIGURE 16-7. Methylmercury, discharged by a chemical factory at Minamata, Japan, and concentrated in fish and shellfish tissues, caused a major pollution problem in the 1950s. (a) Map of the locations around Minamata where diseased cats and dead fishes were reported many kilometers away from the discharge point. (b) Detailed map of the Minamata city area identifying the locations where humans lived who were confirmed to have contracted the "disease." (c) Forty-six people died of mercury poisoning, and many more suffered lasting effects. Even after the early poisonings, the Chiso Chemical Corporation continued to increase its production of acetaldehyde and its waste byproduct, methylmercury. Poisonings continued for years after the release of mercury from the plant was eventually curtailed.

fer widely in composition among industries and even among factories within an industry. Most of these wastes contain various potentially toxic chemicals. A few decades ago, most industrial wastes were discharged to sewers or a local waterway or dumped in a nearby landfill.

The U.S. and most other nations have had laws for several decades to control contaminant discharges to aquatic environments. Enforcement of most of these laws has focused on industrial discharges and sewage treatment. Industries have been required to reduce drastically the concentrations of contaminants in their liquid effluents before discharge. Most industries have changed technologies to reduce the amount of wastes they generate and avoid or reduce the expense of treating effluents.

As a result of decades-long efforts to reduce toxic substances, nutrients, and other contaminants in industrial effluents, industry is now only a minor contributor to the contamination of estuaries and coastal oceans in most areas. Problems remain with some older industrial plants, with industrial discharges that are poorly located where residence time is long, and with the enforcement of discharge permits at a few plants whose unscrupulous owners or operators find ways to discharge wastes illegally. Nevertheless, the general public mistakenly still believes that industry is the principal polluter of the marine environment. There are several reasons for this misunderstanding. The most important is probably that it is easier for the media, politicians, and the public to blame industry for pollution problems than to face the difficult problems of cleaning up individual actions, homes, public utilities, and farms. Another reason is that the only demonstrated and confirmed incident in which the discharge of toxic chemicals to the oceans caused human deaths involved industrial effluents.

For many years, Chiso Chemical Corporation in Minamata, Japan, generated an organic form of mercury, methylmercury, as a by-product of its manufacture of acetaldehyde using mercury as a catalyst. A small portion of the methylmercury was discharged continuously to Minamata Bay in wastewater. Mercury, a toxic metal, accumulated in water, sediments, and fishes. Because methylmercury is more fat-soluble than elemental mercury and is biomagnified (**CC18**) in marine food webs, its concentration in fishes rose to very high levels.

The discharge of methylmercury to Minamata Bay started in 1952. By 1953, many cats were becoming ill, behaving erratically, and dying. Dead fishes were periodically found floating throughout the region (**Fig. 16-7a**). At the same time, some of the human population contracted a puzzling "disease" that produced numbness, disturbances in vision and hearing, and loss of the control of motor functions, similar to drunkenness. The "disease" quickly assumed epidemic proportions, and between 1953 and 1962 more than 40 people died and as many as 2000 other victims suffered what has later proven to be a persistent disability (**Fig. 16-7b**). In 1957, it was found that "Minamata disease" could be induced in cats by feeding them fishes taken from near the Chiso plant outfall. Although fishing was quickly banned, the discharge of methylmercury was not stopped until 1968, because Chiso denied that methylmercury caused the disease until it was overwhelmed by the weight of scientific evidence.

Minamata is apparently the only documented case of human deaths caused by industrial inputs to the marine environment, but a number of cases of deaths of fishes and other marine organisms caused by industrial effluents have been documented. For example, the Montrose Chemical Corporation in Los Angeles produced about two-thirds of the world's DDT in 1970. Starting in 1953, the plant discharged effluent containing DDT through a sewer to Santa Monica Bay. By 1970, this and other sources of DDT, which is fat-soluble and biomagnified, had caused the total collapse of many species at the top of the food web. It particularly affected pelicans, whose eggshells were so thinned by the DDT that they broke before hatching, and sea lions, which produced large numbers of stillborn offspring. DDT discharge was stopped,

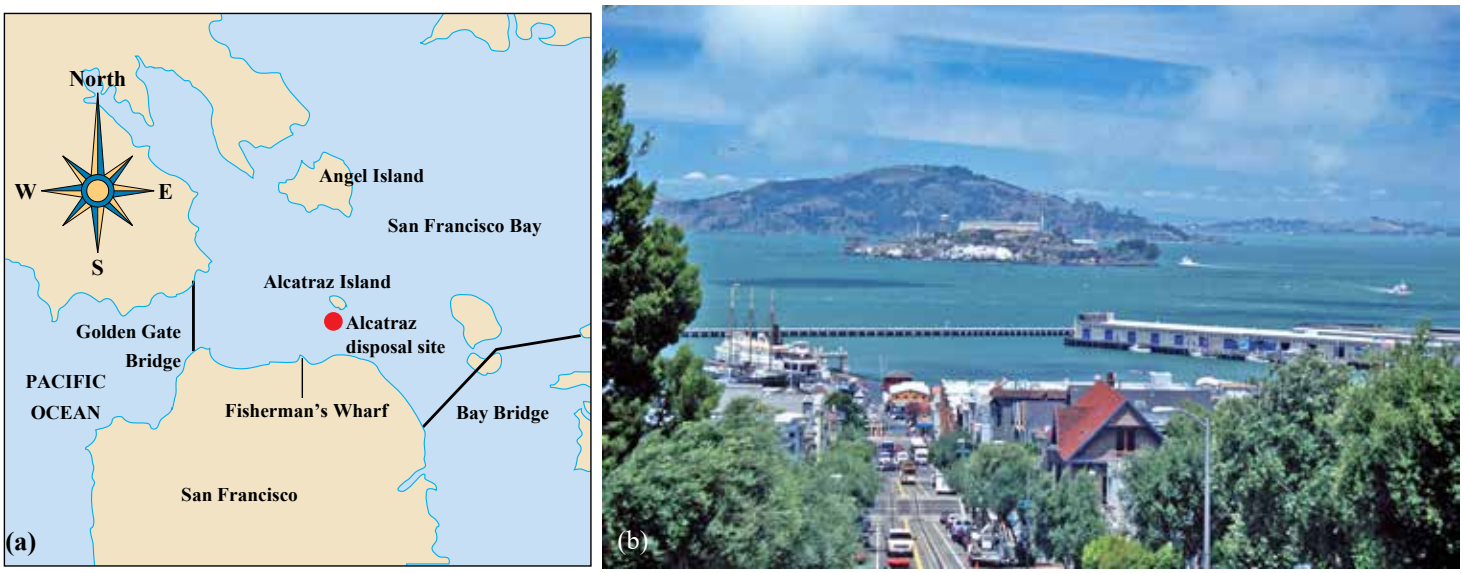


FIGURE 16-8. Dumping of dredged material in San Francisco Bay. (a) The Alcatraz dredged-material dump site in San Francisco Bay is located close to the estuary mouth and to the city of San Francisco. (b) The dump site, which is located between Alcatraz Island and the shoreline in this photograph, is only a few hundred meters from one of the famed tourist attractions of San Francisco, Fisherman's Wharf, and it is within easy view from much of the city.

and the use of DDT was banned in the United States and Europe early in the 1970s.

Pelican, sea lion, and other affected populations have slowly recovered in the decades since the DDT ban. However, DDT and its persistent and toxic decomposition products can still be found in elevated concentrations in sediments and the biota of the southern California coastal zone. Unfortunately, despite its ban in the United States and many other countries, estimates suggest that more DDT is produced and used today than in 1970. Most of it is used for mosquito and malaria control in developing tropical countries that cannot afford more costly and less effective alternatives to DDT, especially since the resurgence of malaria since the 1990s.

Dredged Material

With the exception of a few deep-water ports, most ports and harbors do not have sufficient natural depth for vessels to navigate safely and berth. Consequently, most ports and harbors must be dredged to increase navigable depth. Once sediments have been removed to deepen a channel or basin, suspended sediments tend to settle in the new **topographic** depression. Therefore, all dredged channels and harbors must be re-dredged periodically to remove newly accumulated sediment. In some high-energy regimes where the new channels are regularly swept by currents, or areas where very little suspended sediment is transported to refill the channel, dredging may be necessary only once every several years. However, other channels must be dredged more often, and some require almost continuous dredging.

Dredging is done either by scooping up buckets of sediment or by sucking sediment from the seafloor through a pipe lowered from a surface vessel. In most cases, the dredged material is loaded onto barges and transported to another location before being dumped into an estuary or the ocean.

Dredging destroys the benthos, causes increased turbidity, and, if the dredged material is contaminated, releases toxic substances into the water and suspended sediment at both dredging and dumping sites. These effects may be serious at some dredging sites, but they are generally more damaging at the disposal site. The U.S. has more than 150 aquatic disposal sites for dredged material. Most are in bays or coastal waters very close to the mouth of the estuary from which the material is dredged.

When dredged material is dumped, it descends quickly until it strikes the seafloor. Upon impact, it spreads rapidly across the seafloor as a suspended sediment cloud. Coarse-grained materials settle out quickly. Some smaller particles are partially buried with the coarse-grained material, and others are carried off by currents and deposited elsewhere where current speed is slower. Most or all benthos in the area buried by the dredged material are killed. The area is recolonized over the next few weeks or months except where the dredged material is badly contaminated with toxic substances or if dumping is frequent or continuous.

Because most dredged material consists of sediment taken from channels close to industrial and urban areas, it is usually contaminated with toxic substances from urban runoff, industrial discharges, sewage, and spills. Dumping at most dredged-material dump sites is continuous or is done several times each year. Consequently, the bottom at almost all such dump sites is covered with contaminated sediment, and the benthos is severely damaged on a continuing basis.

A proportion of the fine-grained contaminated dredged material is released as suspended sediment during dumping. Because the contaminants associated with these particles will be at least partially **bioavailable**, dredged material can contribute substantial quantities of toxic substances to the marine environment. For example, until the 1990s the amount of several toxic contaminants dumped annually at the dredged-material dump site near Alcatraz Island in San Francisco Bay (**Fig. 16-8**) exceeded the combined total annual input of these toxic substances to San Francisco Bay from more than 100 industrial and treated sewage discharges. Some of the dredged material previously dumped at the Alcatraz site has now been diverted to disposal on land or at a deep-ocean dump site.

At some dump sites, very heavily contaminated dredged material is covered within a few days by a cap of clean, sandy dredged material several tens of centimeters deep. Once under

this cap, contaminants are effectively removed from the biosphere, but it is not clear what fraction of the contaminants, especially those associated with fine-grained materials, escape before being capped or whether erosion caused by waves and currents eventually breaches the cap.

Most dredged-material dump sites are located in low-current areas to ensure that as much of the dumped material as possible is retained at the site. However, at some sites, such as the Alcatraz dump site in San Francisco Bay (**Fig. 16-8**), with its fast tidal currents, all but the largest dredged particles are resuspended and swept away soon after their disposal. Alcatraz and other similar dump sites were originally selected near estuary mouths because it was asserted that the dumped material would be quickly swept to sea by the river flow. Unfortunately, the dredged material dumped at many such sites, including the Alcatraz dump site, is instead transported back into the estuary by estuarine circulation (**Chap. 13**).

The practice of dredging and dumping the dredged material within estuaries has two important effects. First, the material is partially transported back to, and deposited at, dredging sites within the estuary, thereby increasing the frequency and cost of dredging. Approximately 40% to 50% of the dredged material dumped at the Alcatraz site returns to dredging sites and must be re-dredged. Second, contaminants that were discharged to estuarine sediments decades ago, when waste discharges were largely uncontrolled, are continuously re-dredged, dumped, and resuspended within the estuary, where they come into contact with the biota. The Alcatraz site has been used for dumping dredged material since the 1890s. Since that time, the once extremely valuable commercial fish and shellfish populations of San Francisco Bay have been largely destroyed. Dredged material dumping has undoubtedly contributed to their decline.

Even if treatment techniques were available, treating estuarine sediments to remove historical contamination would not be possible because the sediment volumes are too large. In addition, land disposal of the dredged material is practical only in a few locations, and then only if the material is not contaminated. However, if dredged material disposal sites were moved offshore, beyond the biologically critical coastal zone, the contaminated material, especially if properly capped, would have less environmental impact on the limited benthic communities of the outer continental shelf and continental slope. In addition, if dredged material were dumped in the ocean, and if contaminant source control continued in the estuaries, contaminant concentrations in the estuaries would decrease, and dredged material eventually would be clean enough to be used for beneficial purposes on land.

Plastics and Trash

Although plastics are now known to be decomposed by bacteria in the oceans, they decompose very slowly in the environment. However, some plastic debris first breaks down into smaller particles that can be mistaken for food and eaten by marine organisms. Many species can neither digest the particles nor pass them through the gut, and plastic particles can accumulate in the gut until it is blocked, leading to starvation and death. Larger fragments of plastics are ingested by large animals, especially turtles, which mistake plastic bags and other plastic debris for their favorite food, **jellies**. Plastic fishing line, six-pack rings, plastic fishing nets, and all kinds of other plastic debris act as drifting traps that entangle and kill turtles, birds, and marine mammals (**Fig. 16-9a**).

It has been found that microscopically small plastic fragments are ubiquitous in recent marine sediments and seawater. These fragments have been found in preserved plankton samples from the 1960s, and examination of more recent samples shows that their concentration has increased significantly since then. Adverse effects of plastic ingestion have been observed in larger animals that ingest relatively large particles of plastic (**Fig. 16-9b**), and there is substantial evidence that the ubiquitous microscopic fragments have adverse effects on zooplankton and benthic animals.

International law now prohibits the disposal of plastics in the oceans, but enforcement of this prohibition is virtually impossible, and violations are common. Plastic also reaches the oceans from many sources other than direct disposal, including storm-drain runoff and helium-filled balloons released at sporting events and other festive occasions.

In the 1980s, it was discovered that there was a large area at the center of the North Pacific subtropical gyre where floating plastic debris collects, carried into the center of the gyre by the Ekman transport processes described in **Chapter 6**. Subsequently, similar concentrations of plastic debris have been found in the

FIGURE 16-9. Plastics can cause more than just aesthetic problems in the marine environment. (a) This northern fur seal pup is entangled by a section of lost or discarded gill net and would not have survived long without human intervention. (b) The remains of a dead Laysan Albatross chick (Phoebastria immutabilis) show the large variety and quantity of plastics that it had ingested. The ingested plastics were likely at least a contributing cause to the chick's death.

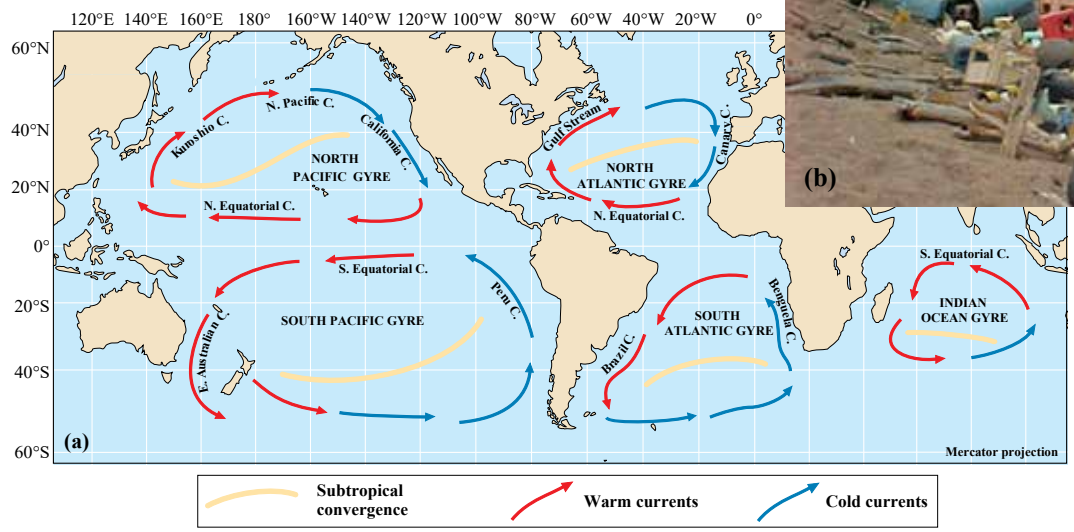


Figure 16-10. (a) Plastic debris collects in the subtropical convergence zones at the center of each of the subtropical gyres. The largest concentration is apparently in the center of the North Pacific gyre and has been dubbed the "Pacific Garbage Patch." (b) Plastic debris also washes up on the beaches of islands, such as the Hawaiian Islands, that are located within the subtropical gyres.

centers of each of the five subtropical gyres (Fig. 16-10a). The area of greatest plastic debris concentration has been referred to as the North Pacific garbage patch, and the media have portrayed this area as being a huge visible debris field. However, this is a significant mischaracterization since the debris in most of the affected region (and affected regions in the four other subtropical gyres) primarily consists of particles that are generally invisible to the naked eye, with usually widely scattered larger plastic pieces or items. Nevertheless, the accumulation of plastic debris in these mid-ocean regions poses a threat to at least some marine organisms and birds. Since 1980, substantial efforts have been made in most countries to reduce the amount of plastics that enter the oceans, but these have only had modest success. There are also ongoing studies investigating how plastic debris might be collected and removed from the centers of the gyres. However, the amount of plastics is very large, and most of it is widely dispersed, so any removal efforts will be extremely costly and difficult.

Metal, paper, and other trash items cause fewer problems in the ocean than plastics because they eventually corrode or decompose. Nevertheless, these discarded materials, including plastics, cause aesthetic problems when they wash up on beaches and shores or litter the seafloor that divers visit (Fig. 16-10b). Included among the floatable wastes are medical wastes, such as syringes, illegally discarded from vessels and into rivers and storm drains. These wastes have led to precautionary beach closures when they wash ashore. Storm drains are considered to be the primary source of most types of floatable wastes present in the oceans.

Antifouling Paints

Unless protected, almost any surface introduced into the ocean is quickly covered, or fouled, with a wide variety of marine animals and algae. Barnacles have an especially strong natural adhesive that enables them to attach and hold on to surfaces even in swift currents that can sweep off other fouling organisms. Hence, barnacles dominate the fouling community on vessel hulls and on structures in strong currents.

When a normally smooth vessel hull or other moving surface is fouled, **friction** between the hull and water increases, causing the vessel to either lose speed or use more fuel to maintain speed. Consequently, vessel hulls, turbines of tidal power plants, and water intakes and drainpipes must be protected from fouling.

The predominant and most effective means of reducing fouling is to coat the substrate with paint containing a toxic substance that will kill any organism that settles. The toxic substance must be bioavailable to perform its function, so the paint must release its toxic substance slowly into solution. Consequently, vessels and other structures release these toxic substances to the marine environment, causing an especially serious problem in harbors where boats are concentrated and water residence times are long.

For many years, most antifouling paints contained copper as their active toxic ingredient. Copper is highly toxic at moderate concentrations in its ionic form. However, at lower concentrations, it is nontoxic and readily **complexes** with organic matter, reducing its toxicity. Thus, as copper is released from an antifouling paint, it has the desired antifouling action, but it is quickly diluted and complexed with natural organic matter as it **diffuses** away from the treated surface. Copper does accumulate in the water of harbors and marinas, but adverse impacts on biota other than those fouling the painted surface have been extremely rare.

Although copper-based antifouling paints are effective, their effectiveness diminishes as the copper progressively dissolves. To reduce the frequency with which ships' hulls must be cleaned and repainted, a more effective antifouling paint was developed in which tributyltin replaced copper. Tributyltin is much more toxic than copper and is released more slowly from antifouling paints. Hence, each application of tributyltin-based paint was effective for a longer period than an application of copper-based paint.

Unfortunately, once released into the water, tributyltin is degraded only slowly into a less toxic chemical form. Conse-

quently, it retains its toxicity and tends to concentrate in the water in areas where many boats have such paints. Tributyltin has caused serious marine pollution problems in some areas. Many ports and marinas where tributyltin paint was used extensively were essentially denuded of all animal life. Because tributyltin is particularly toxic to **mollusks**, it destroyed populations of oysters and other species over a wide area far from its source in some estuaries. There has been a worldwide ban on the use of tributyltin-based paints since 2008. Fortunately, unlike DDT, tributyltin does not persist in the environment for decades. Rapid recolonization and recovery have occurred in many areas previously affected by tributyltin.

Radionuclides

Among the most feared words in the English language are nuclear, radioactive, and radionuclide. This is, of course, because most people associate these terms with nuclear bombs. As a result, during the nuclear testing era from 1945 to about 1990, there was considerable attention, both by the public and among environmental researchers, to the introduction of radioactive materials to the environment, including the oceans, of radioactive fallout from nuclear tests. Dumping of radioactive wastes and discharges or accidental releases from nuclear industrial facilities. Some of the radionuclides from these sources do not occur naturally on Earth. Public fears of radioactive materials in the environment were heightened by a nuclear power plant accident in Chernobyl, Ukraine in 1986 and further exacerbated by the severe damage of several nuclear reactors near Fukushima Japan in 2011 following a massive earthquake and tsunami.

There has been extensive research on the effects of radioactive material from nuclear bomb test fallout, and radioactive materials discharged or dumped, either deliberately or as a result of accidents. The results of this research are summarized in **Online Box 16B3**, and the principal findings are summarized here.

1. In the marine environment, radionuclides enter **biogeochemical cycles** and behave in the same way as the stable **isotopes** of their elements (if stable forms exist).
2. Each element and its **radioisotope**(s) have their own distinct behavior in the oceans. For example:
   a. Tritium (hydrogen-3), released in nuclear explosions, quickly combines with oxygen to form water molecules that join the ocean circulation system, where they behave almost exactly as other water molecules do.
   b. An iodine radioisotope, iodine-131, enters solution in ocean water and is concentrated by marine biota, particularly certain species of algae.
   c. Plutonium does not occur naturally but is rapidly attached to particles in the ocean environment. Most plutonium is carried to sediments by these particles, where it remains until it decays to other elements.
3. Radioisotope concentrations are easily measured even in environmental samples that contain only a few atoms of the isotope. For this reason, radioactive isotopes are used as **tracers** to study geochemical, biological, and physical processes in the oceans (**Chap. 8**). They are also commonly used as tracers in biological systems, including human medical scans.
4. Radioactivity can have adverse effects on marine ecosystems and on human health, primarily because some anthropogenic radioisotopes concentrate in seafood and increase the risk of cancer in consumers.
5. Except for very limited areas surrounding some nuclear bomb testing sites, concentrations of anthropogenic radioisotopes in seafood are well below background levels of naturally occurring radioactive elements.
6. The accepted theory of carcinogenicity is that any increase in radioisotope intake will increase the risk of cancer. The oceans' assimilative capacity for anthropogenic radioactive materials may therefore be zero. In reality, a very small increase in radioactivity above natural background levels will not produce a measurable or significant increase in cancers.
7. Because the ocean's assimilative capacity for radioactive materials is so small, international agreements require that anthropogenic inputs be eliminated. Almost all nations adhere to these agreements.
8. A very small amount of liquid radioactive waste continues to leak from the Sellafield nuclear industrial complex in Sellafield, Northern England.
9. The former Soviet Union routinely dumped and discharged large quantities of solid and liquid radioactive waste into the Arctic Ocean, the Sea of Japan, and rivers that empty into the Arctic Ocean, until 2005, when Russia agreed to the global treaty that bans these practices.
10. In 2011, the Fukushima Daiichi nuclear power reactors in Japan were damaged by an earthquake of magnitude 9.0 (a once in a century occurrence) and the more than 40 m-high tsunami it caused (a once in a thousand years occurrence). Large quantities of water containing radioactive elements were eventually released into the oceans.
    a. Studies showed that radioactivity levels rapidly reduced with distance from the reactors.
    b. Within five years, levels were too low for any adverse effects to be found in any marine organisms studied (ranging from microalgae to mollusks and fishes), even in ocean areas close to the accident site.
    c. The major impact on the oceans appears to have been the precautionary closure of the area to fisheries.

Fears of radioactivity releases fueled by media accounts of the Fukushima and Chernobyl, Ukraine (1986) power plant accidents, and a 1979 accident at Three Mile Island in Pennsylvania (that released small amounts of radioactivity to the atmosphere) have caused public perception to conclude that nuclear power plants are unsafe and nuclear power should not be used in the future. While these fears are understandable, they are not based on scientific facts.

1. At present, there are about 420 nuclear power plants operating worldwide, and these provide about 9% of the world's electrical power generation capacity and needs.
2. Nuclear power is the only electricity-generating technology that is
    a. Free from carbon dioxide emissions to the atmosphere,
    b. Operates 24 h per day and can be operated at variable levels to meet hourly demand fluctuations, and
    c. can provide city-scale amounts of power from a single plant with a small land-use footprint.
    d. Has a long history (since the 1950's) of safe operations. The Chernobyl accident occurred at a poorly designed Soviet reactor with no safety containment vessel. The Fukushima accident was caused by one of the most powerful earthquakes, plus one of the largest tsunamis in human history. No other major accidents have occurred that have

caused deaths or significant radioactivity exposure beyond a small number of plant employees.

3. Waste disposal is a significant issue with nuclear power. However, there are breeder reactors that reduce the radioactivity of waste from other nuclear power plants, or wastes could be placed in safe storage and disposal sites. Disposal sites must be located where wastes will remain undisturbed until radioactivity is reduced to background levels. The best such geologically stable long-term storage locations may be beneath the sediments in the center of oceanic tectonic plates. Technologies to emplace radioactive waste deep within ocean sediments were extensively researched and developed in the U.S. in the 1970s. This research was abandoned after the London Dumping Convention adopted a ban on all disposal of wastes in the oceans in 1975.

Noise

The ocean environment has always been noisy, with sounds generated by many marine species that use sound for communication or other purposes (**Chap 14**) and by rain, waves, and earthquakes. However, the oceans are becoming progressively noisier due to sound from ships, offshore resource extraction, including offshore oil and gas development, from military and civilian use of sonar, and from seismic surveying. Very little is known about the individual sources of sound in the oceans or about how anthropogenic noise may affect marine species. However, there is concern that anthropogenic noise may adversely affect some species, especially marine mammals that communicate and navigate by using sound.

In March 2000, 14 beaked whales and two minke whales became stranded on beaches in the Bahamas after they were exposed to sound emitted by the U.S. Navy in testing of a new high-intensity, mid-frequency sonar. Six of the beaked whales died and were found to have internal bleeding that apparently resulted from close-range exposure to the high-intensity, mid-frequency sonar. As a result, use of this sonar, which uses higher intensity than other anthropogenic sound sources and a frequency not used in other sonar applications, has now been severely restricted. Precautions are now taken to ensure that no marine mammals are within a wide exclusion zone whenever this sonar, which is believed to be essential for national security, is tested. Also, as a result of the finding that excessive sound can harm marine mammals, ongoing research aims to study the effects of all anthropogenic sounds in the oceans.

Nonidigenous Species

Marine species are transported around the world in ships' ballast water, attached to ships' hulls, and in other unintended ways. Species are also deliberately transported from one location to another to be used in aquariums or for aquaculture, and many of these are inadvertently or deliberately released to marine ecosystems in which they do not occur naturally. Once in their new environment, these species may die if they are unable to tolerate the new conditions or avoid their new predators, or they may survive and reproduce with little effect on the rest of the ecosystem. However, some nonindigenous species not only survive but also reproduce, spread rapidly, and out-compete native species. Estimates suggest that approximately 15% of introduced species cause severe harm to their new environment.

Many examples can be given of nonindigenous species that have severely damaged terrestrial and freshwater ecosystems. Fewer examples of damage are known in the marine environment, probably for several reasons. First, marine biota are not as easily observed as freshwater and land biota; thus, adverse changes due to nonindigenous species may not be noticed. In addition, because the ecology of marine ecosystems is poorly known, declines of important species and other ecological changes may be attributed to other factors, even if caused by nonindigenous species. Open-ocean ecosystems are generally well connected with each other and more uniform than terrestrial or freshwater ecosystems. However, coastal marine ecosystems, especially estuaries, are more isolated from one another and therefore more vulnerable to the introduction of nonindigenous species.

San Francisco Bay is an excellent example of an estuary that has been severely damaged by nonindigenous species. It is the only major estuary on a long stretch of coast, and as a result, it is isolated from other estuaries. Therefore, the Bay had many unique species when European settlers arrived. The settlers deliberately introduced nonindigenous species, such as the eastern oyster (*Crassostrea virginica*), in an attempt to populate the bay with valuable food species. The oyster did not survive, but a variety of other species brought in with the oyster, either attached to its shell or in the seawater in which it was transported, did become established.

Eastern oysters were the first of many introductions. Among these introductions, one notable species was striped bass, which became a major anadromous sport fish. However, the striped bass competes for food and habitat with indigenous species, such as salmon and sturgeon. These and other introductions of nonindigenous species into San Francisco Bay have caused dramatic changes. Most original species in the Bay are now gone, and the majority of species present today were introduced. For example, almost half of the fish species in the critical wetland habitat are nonindigenous. Nearly all invertebrates that now inhabit shallow, nearshore parts of the Bay are also non-indigenous. Indigenous clams and other edible mollusks have been largely replaced by a small, economically valueless species of Asian clam.

Habitat Alteration

Alteration or destruction of habitat is among the most damaging forms of pollution in estuaries and the coastal zone. The most serious habitat destruction is the filling of wetlands to create dry land. An estimated 450,000 km^2 (almost 50%) of the historical wetlands of the U.S., excluding those in Alaska, have been lost since European settlers arrived. In some areas, such as San Francisco Bay, less than 10% of the historical wetland area remains (**Fig. 16-2**). Many tens of thousands of acres of wetland habitat for aquatic birds, juvenile fishes, and other species have been lost. Other forms of adverse habitat alteration or loss include beach erosion or loss due to coastal structures (**Chap. 13**), dredging of channels through mudflats, burial of seafloor by dredged material, and damage to coral reefs by anchors.

Less obvious habitat alteration is caused by human activities that lead to changes in salinity, temperature, and turbidity. Soil erosion has increased in many watersheds because trees and other vegetation have been removed. Increased suspended sediment loads have altered sediment grain size in many rivers, making the sediments unsuitable as **spawning** habitat for anadromous fishes. Excess turbidity has reduced light penetration and thus rendered both benthic and pelagic habitats less suitable, or unsuitable, for algae growth, with resultant effects throughout the food web. For example, more than 90% of the historical **sea grass** cover has

been lost in Galveston Bay, more than 75% in Mississippi Sound, and more than 50% in Tampa Bay.

Reduction of freshwater flow into estuaries is a particularly serious form of habitat alteration. In many estuaries, species zonation is based on the salinity distribution. For example, plants rooted in freshwater are replaced by saltwater species in the lower parts of the estuary, where salinity is higher. If freshwater inputs are drastically reduced, as when rivers are dammed, salinity ranges can be shifted many kilometers up an estuary, dramatically altering the balance between freshwater-dominated and seawater-dominated habitats.

In some estuaries, such as San Francisco Bay, freshwater input reductions have caused the critical **brackish** water zone, where much estuarine productivity occurs, to migrate from a wide wetland-fringed part of the estuary into a deeper, narrower, faster-flowing section. Primary productivity has been lowered because of the smaller area of suitably brackish water and the high turbidity. Such loss of primary productivity may have contributed to dramatic declines in anadromous fish species in this and other estuaries. Reduction of freshwater inflows also tends to increase residence times within the estuary. Consequently, contaminants have longer residence times and reach higher concentrations.

Fishing

Far from being the traditional environmentally friendly activity that it is often portrayed to be by the media and thought to be by the general public, fishing is acknowledged by most marine scientists to be the human activity that has caused more adverse impacts on the oceans than anything other than anthropogenic releases of carbon dioxide and nutrients. Fisheries and overfishing, their principal impact, are discussed in **Chapter 2**.

Fishing, particularly commercial fishing and subsistence fishing in some nations, contributes to ocean contamination or pollution in many ways beyond overfishing. The most significant impact of fishing on ocean environments is the habitat disturbances and destruction caused by trawl fishing for fish and shellfish that involve dragging nets across the seafloor. Trawling generally destroys or collects all epibenthos, including delicate and extremely slow-growing deep sea corals, which take centuries to regrow even if they can recolonize the altered seafloor sediments.

Large quantities of fishing gear, including fishing line, fishing nets, and Styrofoam floats, much of which are made from plastics, are lost and can have adverse effects on marine organisms, as discussed earlier in this chapter. This lost or discarded fishing gear is so widespread and problematic that the media often refers to it as “ghost gear.” In addition, vessels intentionally or accidentally discharge oil and diesel fuel, oily bilge waters, sewage, and food and packaging wastes. Such discharges are regulated or banned by many nations, including the U.S. However, as is true of fishing regulations, anti-discharge laws are difficult to enforce on the high seas, and especially difficult in those areas that are not part of any nation’s exclusive economic zone (EEZ), where many of these laws do not even apply. Fishing vessels also have hull paints that contain toxic chemicals to combat fouling by organisms such as barnacles, and these toxic chemicals can damage fishery resources.

CLIMATE CHANGE, ACIDIFICATION AND DEOXYGENATION

The global radiation budget is not currently in equilibrium. The imbalance between heat energy entering and leaving Earth’s atmosphere is difficult to measure because it varies with the sun’s energy output, which varies in short term to decadal and longer cycles time scales. However, it has been estimated that in 2025 Earth radiated to space about 1.2 W/m^2 less energy than it receives from the Sun, creating an imbalance of 0.35% of the total incoming solar radiation at the top of the atmosphere. This imbalance is estimated to be growing at a rate of about 0.045 W/m^2 per year. In response to this radiation imbalance, additional energy is accumulating in Earth’s climate system and Earth is warming. Satellite sensors and instrumented buoys and floats at sea show an accelerating increase in heat content of the upper 2 km of the ocean since the 1970s.

Because Earth’s climate system has considerable thermal inertia, which is mostly due to the ocean’s high heat capacity, a considerable length of time is required for Earth’s climate system to achieve equilibrium under new environmental conditions. Unless there are unforeseen changes (such as a major increase in global volcanic activity) global climate models predict that rising concentrations of atmospheric carbon dioxide and other greenhouse gases will cause global warming to persist through this century and beyond. Even if greenhouse gas emissions were to stabilize at present levels, global warming would continue well beyond the 21st century. The magnitude of warming will depend on the rate of continued greenhouse gas emissions and related feedbacks.

Climate change is geographically non-uniform in both magnitude and sign so the rise in global mean annual temperature predicted by global climate models does not represent what might happen everywhere. Climate models predict polar temperature amplification, meaning that warming will be greater at higher latitudes.

The residence time of carbon dioxide in the atmosphere is between about 300 and 1000 years. The slow rate of removal of carbon dioxide from the atmosphere means that, if the rate of carbon dioxide emissions were to stabilize at the current level, the atmospheric concentration of carbon dioxide would still continue to increase. If anthropogenic emissions can be substantially reduced but not eliminated entirely, carbon dioxide would still enter the atmosphere faster than it is cycled out, and the atmospheric carbon dioxide concentration would continue to increase, although at a slower rate. Only the complete elimination of anthropogenic carbon dioxide emissions would stabilize and then, eventually, reduce the concentration of atmospheric carbon dioxide from current levels.

Approximately 40% of the estimated anthropogenic carbon dioxide released into the atmosphere since the beginning of the Industrial Revolution has been absorbed by the oceans. Currently, about 15% to 30% of anthropogenic carbon dioxide gas released to the atmosphere annually is removed from the atmosphere to the oceans. Some of the anthropogenic carbon dioxide absorbed by the oceans is transported to the deep oceans below the permanent thermocline by sinking of cold surface water in the global thermohaline circulation. Some carbon dioxide is also transported to the deep waters by sinking of organic matter produced by photosynthesis in the surface layer. The residence time of ocean deep waters is long, so this carbon dioxide is sequestered for as much as a thousand years before returning to the atmosphere-ocean interface.

Climate change, driven by rising concentrations of atmospheric carbon dioxide and other greenhouse gases, causes ocean

surface waters to warm. Warming increases ocean density stratification and slows thermohaline circulation. Slowing the thermohaline circulation causes deep ocean water to spend longer in the deep oceans, where its oxygen concentration declines steadily due to the transport of organic matter from above and the respiration of decomposers. The amount of organic matter transported to the lower layers of the oceans is increasing due to enhanced photosynthetic primary production in the surface waters, which is due to higher concentrations of carbon dioxide and nutrients introduced by humans. The increased primary production contributes to declining oxygen concentration or deoxygenation in deep oceans. Absorption of anthropogenic carbon dioxide in ocean water also causes the water to acidify.

Thus, the oceans are subjected to acidification, deoxygenation, and circulation changes all caused by the same anthropogenic activity - carbon dioxide release to the atmosphere. Each of these can cause adverse effects on ocean ecosystems, and the synergistic effects of their acting together can be severe. Potentially so severe that this combination of rapid change in atmospheric greenhouse gases, ocean acidification, and deoxygenation of the deep oceans has been associated in the historical record with most, if not all, of the five major mass species extinctions that have occurred in Earth's 4 billion year history. The possibility that our anthropogenic releases of carbon dioxide could be driving the ocean ecosystem toward another mass extinction is both real and serious. The consequences of a 6th mass species extinction to humans and Earth's ecology would be catastrophic beyond anything that could possibly be caused by any of the other ocean pollution issues discussed in this chapter. Consequently, we discuss these three interrelated issues together in this section.

The Oceans and Climate Change

The ocean is the largest heat sink in Earth's climate system and has been found to contain more than 90% of the additional heat energy captured by Earth due to anthropogenic greenhouse gases. About one-third of this heat energy is now in the deep ocean (below 700 m). Since 2005, the rate of total anthropogenic heat accumulation in the deep ocean has exceeded the rate in the upper layer (0 to 700 m).

Models predict that the ocean will continue to warm during the 21st century, with the strongest ocean warming projected to occur in the surface layer in tropical and Northern Hemisphere subtropical regions. At greater depth, the warming will be most pronounced in the Southern Ocean.

Temperature and Salinity Changes in the Oceans

Atmospheric global warming has accelerated in recent years, with the top 10 warmest years occurring since 2015. Since 1979, the rate of warming has been about 0.20±0.02°C (0.36±0.04°F), resulting in approximately 0.9°C (1.6°F) of warming over the last 45 years. The atmospheric warming has been accompanied by the warming of ocean waters

A warming atmosphere and ocean surface lead to a redistribution of rainfall and ocean salinity patterns. Salinity increases in regions where there is increased evaporation of ocean water. Conversely, increased inputs of fresh water from rivers, precipitation, and melting ice decrease salinity. Observations show that mid-latitude surface ocean water has become saltier, indicating the evaporation rate has increased in this zone. Surface waters in tropical and polar regions have become less salty. In other words, the moisture surpluses from the mid-latitudes condensed into liquid that precipitated in nearly equal amounts in these tropical and polar regions. This pattern is expected to lead to weakening of the meridional overturning circulation, impacting the climate of northern latitudes, contributing to increasing deoxygenation of the deep water layers of the ocean, as discussed in more detail later in this section.

Polar Regions

Polar temperature amplification means that the current global warming trend is greater at higher latitudes. Amplification of warming at higher latitudes threatens the ice sheets of Antarctica and Greenland. About 90% of Earth's glacial ice blankets Antarctica, and melting this glacial ice would cause a catastrophic rise in sea level.

Two ice sheets cover most of Antarctica, separated by the Transantarctic Mountains. The larger of the two, the East Antarctic Ice Sheet (EAIS), is situated on a continent about the size of Australia, averages about 2 km in thickness, and accounts for two-thirds of Antarctic ice. Complete melting of the EAIS would raise mean sea level by about 60 m, although such large-scale melting is highly unlikely to occur under the climate predictions that are deemed likely during the next century or so, which depend on assumptions of future global carbon dioxide emissions. Geological evidence suggests that the EAIS has been stable for the past 30 million years and remains fairly stable today. However, it has undergone episodes of rapid disintegration and may have completely melted at least once in the past 600,000 years. The West Antarctic Ice Sheet (WAIS) sits on a series of islands and the floor of the Southern Ocean, with parts of the ice sheet more than 1.7 km below mean sea level. Complete melting of the WAIS would raise mean sea level by an estimated 5.8 m.

Researchers have concluded that the annual temperature of West Antarctica increased by about 0.20±0.18°C (0.35±0.32°F) per decade between 1957 and 2024: one of the fastest-warming regions on the globe. This warming has been accompanied by higher SSTs around Antarctica and the breakup of ice shelves along the Antarctic Peninsula coast. The majority of glaciers of the Antarctic Peninsula are retreating at an accelerating rate. In fact, the melting rate for the WAIS has tripled over the last 10 to 15 years. Scientists find that the section of the WAIS with accelerated melting appears to be in persistent decline, which will lead the glaciers in this area to melt into the ocean and cause global sea level rise. The question is whether that occurs sooner or later (that is, centuries or millennia).

Unlike the Antarctic ice sheets, which are polar (cold), the Greenland Ice Sheet is temperate. While the Antarctic ice sheets are well below the pressure-melting point (temperature at which ice melts at a given pressure), the temperature of much of the ice on Greenland is near the pressure-melting point. The melting point of ice decreases with increasing confining pressure (or depth within the glacier). Temperate ice sheets more readily generate meltwater and, with less frictional resistance, tend to flow downhill faster than polar ice sheets. The Greenland Ice Sheet has exhibited accelerated melting, and indications are that this melting rate might accelerate even further. Complete melting of the Greenland Ice Sheet would raise mean sea level by an estimated 7.3 m. The consequences of sea level rise are one of the most important adverse effects of climate change on human civilization.

Another major concern associated with the current global warming trend is shrinkage of Arctic sea-ice cover. Arctic sea-ice cover is shrinking at an accelerated rate so that the Arctic Ocean

may be free of summer ice within a few years or decades. Although melting of floating sea ice does not raise sea level, it can alter climate significantly. Less sea-ice cover on the Arctic Ocean is causing the humidity of the overlying air to increase, leading to more cloudiness. Clouds cause both cooling (by reflecting sunlight to space) and warming (by absorbing outgoing infrared radiation and emitting infrared radiation in all directions, including some directed towards Earth's surface). During the long, dark polar winter, additional cloud cover is expected to have a net warming effect. In summer, the impact of greater cloud cover depends on the altitude of the clouds. Cooling would be expected with an increase in low-altitude cloud cover, whereas warming would likely accompany an increase in high cloud cover. The mean annual air temperatures in the Arctic region have increased at a rate of 0.67±0.08°C (1.2±0.15°F) per decade, more than triple the global temperature increase rate.

In addition to shrinking sea ice, Northern Hemisphere snow cover has decreased, mountain glaciers are shrinking, permafrost is beginning to thaw, and fresh water runoff into the ocean has increased. Input of more fresh water from rivers and melting glaciers could impact the ocean thermohaline circulation by reducing the salinity and thus density of surface water in the area where dense, cold, salty water sinks at high latitudes of the Atlantic Ocean to become a critically important part of the MOC. Reductions in the strength of MOC could impact Northern Hemisphere weather patterns and would increase ocean deoxygenation.

Global Mean Sea Level

During the last glacial maximum, about 20,000 to 19,000 years ago, mean sea level was estimated to be 113 to 135 m lower than it is today. Sea level is currently close to the highest level it has been during the past 100,000 years, but it has been substantially higher, as much as several hundred meters higher, during warmer periods prior to that. Sea level falls during ice ages when global temperatures cool, and much of the world's water is stored in glacial ice on land. In contrast, sea level rises when the climate and ocean water warms and glacial ice melts.

The mean rate of globally-averaged sea-level rise between 1901 and 2010 was about 1.7 mm• yr^{-1}, which increased to 3 mm•yr^{-1} between 1993 and 2020. Considering the inertia in the Earth's climate system, it is a virtual certainty that global mean sea-level rise will continue beyond 2100 and that sea-level rise due to thermal expansion will continue for many centuries. Due to the rapid melt now occurring in Greenland and Antarctica and the instability of parts of the Antarctic ice sheet, sea-level rise by the end of this century is expected to range from 0.3 to 1 m, depending on future anthropogenic release rates of greenhouse gases.

The impacts of sea level rise are extensive. Higher mean sea level is expected to accelerate coastal erosion by wave action, allow ocean water to inundate wetlands, estuaries, and islands, and make low-lying coastal plains more vulnerable to storm surges. Rising sea level is also expected to disrupt coastal ecosystems, ruin agricultural lands, threaten historical, cultural, and recreational resources, and displace coastal populations. Ports, airports, and other coastal infrastructure are likely also to be disrupted by rising sea levels, causing large economic losses and extensive costs to either protect them from flooding or relocate them. In some coastal areas, higher sea level is also likely to exacerbate saltwater intrusion into groundwater.

According to a report by the U.S. Office of Science and Technology, a 0.5 m rise in sea level, close to the lower end of the range expected before the end of the century, would result in a substantial loss of coastal land, especially along the U.S. Gulf and southern Atlantic coasts. Particularly vulnerable is South Florida, where the elevation of one-third of the Everglades is less than 0.3 m above sea level. For people currently living on low-lying islands (such as the Maldives and Tuvalu), abandonment appears to be their only option as sea level rises. Globally, 147 to 216 million people live on land that will be below sea level or regular flood levels by the end of this century.

Marine methane hydrates (**Chapter 2**) are not stable at surface temperatures and pressures, but form in pore spaces within ocean floor sediments at depths greater than 400 m, where temperatures are sufficiently low and/or pressures are sufficiently high. When methane hydrates are brought to the surface, the reduction in pressure and rise in temperature cause the hydrates to become unstable and decompose, releasing methane. Warming of ocean water may release methane from methane hydrates and, if large quantities of methane are released and not absorbed by marine organisms before reaching the atmosphere, may contribute to global climate change. Atmospheric methane is a greenhouse gas, more potent than carbon dioxide, although with a shorter lifetime in the atmosphere. If the released methane is consumed by marine bacteria that use it as a food source, this will consume dissolved oxygen and contribute to deoxygenation. Methane concentrations in the atmosphere have been monitored since about 1985 and have indeed been rising, with a faster rate since 2007 than in previous decades.

Marine Ecosystems

Marine organisms are vulnerable to a changing climate. Materials and energy flow from one organism to another via food webs within and between ecosystems. Climate change alters the physical and chemical conditions in the ocean, possibly exceeding the tolerance limits of many organisms. If these organisms are unable to avoid or adapt to these changed conditions, they may individually perish or, as a species, become extinct.

One important example of the vulnerability of marine organisms is the phenomenon of coral bleaching, which is not limited to corals. In addition to hard corals (**Figs. 13-12a,b,c,d**) and sea fans (**Fig. 14-08e**), many mollusks such as giant clams (**Fig. 14-35d**), some flatworms, many anemones, and some protists all host symbiotic zooxanthellae. In response to elevated sea surface water temperatures, zooxanthellae become toxic, and their coral polyps expel them. The specific temperature susceptibility varies with the particular strain of the zooxanthellae hosted by each species. Without the colorful zooxanthellae, the corals appear nearly transparent against the white exoskeleton, so the condition is known as coral bleaching. The same "bleaching" process also occurs in anemones, clams, and other zooxanthellae hosting species.

For reef-building corals, a rise in SST of 1 to 2°C is sufficient to stress the corals, causing temporary bleaching. While corals can recover from bleaching, persistent or severe episodes cause coral polyps and the reef to die. Furthermore, higher ocean temperatures and bleaching make corals more vulnerable to infection and likely acidification, adding to reef mortality. In many tropical coral reef ecosystems, sea surface temperature has been high enough to cause coral bleaching during some El Niño events, but temperatures have been low enough between events to allow the corals to recover. However, as sea surface temperatures have continued to rise, temperatures between El Niño events are becoming

progressively higher, and bleaching has occurred over greater areas every year. As a result, coral bleaching events are becoming more frequent and are now occurring annually. Because the corals no longer have sufficient time to recover between bleaching events, these recurring events often result in the collapse and death of much of the reef. Many reefs have already been observed to collapse and die from coral bleaching.

A key consideration in the potential impacts of climate change on marine organisms is the rate of change. Marine ecosystems can more readily adjust to gradual rather than abrupt changes in the ocean environment brought on by global-scale climate fluctuations. The current rate of climate change due to the enhanced greenhouse effect is approximately 10 times faster than at any time during the past 10,000 years.

Acidification

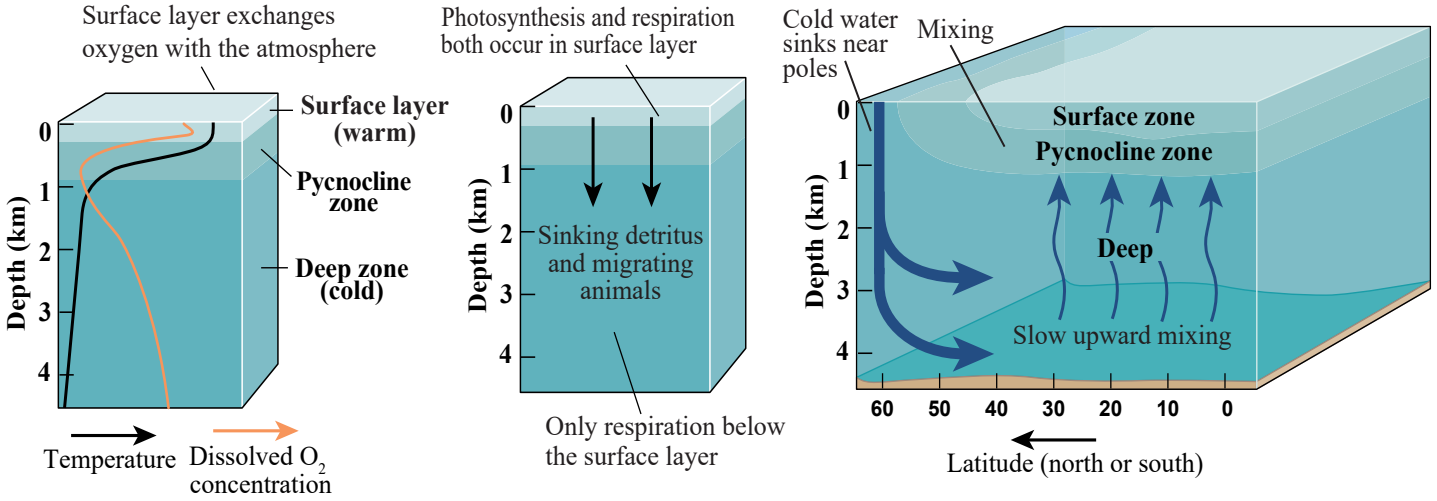
Recall from **Chapter 1**, that as a result of anthropogenically released carbon dioxide, the ocean is becoming more acidic. Evidence shows that at times the ancient ocean was more acidic than today, but modern acidification is happening faster than in the past. Currently, the ocean is still weakly alkaline, but the average pH value has dropped from 8.2 to 8.1 during the past 200 years. This corresponds to a 30% increase in acidity. By 2100, the ocean is expected to be 100 to 150% more acidic than today. This rate of acidification is expected to be too fast to allow many marine species to adapt or evolve. As a result, marine organisms and ecosystems may be adversely affected and many marine species may become extinct.

A more acidic ocean makes calcium carbonate, the material of many hard parts (shells and skeletons) of marine organisms, more soluble and therefore more difficult for marine organisms to grow and maintain. The adverse effects of ocean acidification on marine ecosystems are already significant. In those areas of the ocean where acidity levels are highest, bivalves, marine snails, and other mollusks show decreases in the growth rate of their shells, especially in the early larval stages. Echinoderms, most notably sea urchins, have shown a decrease in fertilization success, developmental rates, and larval size. For vertebrates like fish, the direct impacts are less understood, but recent studies indicate that fish, like invertebrates, are most susceptible at the egg and larval life stages. Research has documented changes in fish behavior and issues with the development of their otoliths, a calcareous structure of the inner ear linked to balance, orientation, and sound detection. These effects, especially when taken together, can disturb food webs and the entire marine ecosystem.

The observed adverse effects of acidification on oysters and pteropods in both the Bering Sea and the California Current off the west coast of the U.S. and Canada are described in **Chapter 1**.

Deoxygenation

Ocean deoxygenation is the loss of dissolved oxygen from the ocean. Multiple sources of observations show that during the past century, oxygen concentration in the ocean has declined. According to research published in 2017, scientists detected a decline of more than 2% in global ocean oxygen content between 1960 and 2010, while some areas experienced a larger drop. For example, the largest volume of oxygen loss occurred in the North Pacific, but the largest percent of decline occurred in the Arctic. A 2% drop may not seem significant, but, similar to the global mean



(a) Layered structure of the oceans. Pycnocline zone is a transition zone where water temperature decreases and density increases rapidly with depth and vertical mixing is slow.

(b) Oxygen is used up by respiration in the pycnocline and deep zones. Rate of respiration is higher just below the pycnocline zone than at deeper depths.

(c) Ocean circulation carries oxygen rich surface water into deep layers. This oxygen rich water is slowly mixed back toward the surface layer while its oxygen concentration is progressively decreased by respiration.

FIGURE 1-3. Oxygen concentration in ocean water is controlled by both physical and biological processes. The oceans consist of two main layers, a warm surface layer and a cold deep layer, with a transition zone, called the pycnocline zone, between them. (a) Surface layer water is well mixed and in contact with the atmosphere, and its oxygen concentration is primarily controlled by gas exchange with the atmosphere. (b) Photosynthesis by marine life in this layer converts carbon dioxide to organic matter and releases oxygen, but this is offset by respiration, which converts oxygen to carbon dioxide. Respiration also occurs in the deep layer, fueled by animals that migrate vertically or live in the deep and decomposition of organic material (detritus), but there is no photosynthesis and no contact with the atmosphere, so respiration continuously consumes oxygen in this deep layer, and, therefore, the longer the water remains in the deep layers, the less oxygen it contains. (c) The deep layer water is continuously replenished by sinking cold water in some near-polar regions and then circulates through the oceans while being slowly mixed upward, eventually into the surface layer again. The pycnocline provides a barrier that inhibits mixing, so the upward mixing process is slow.

annual temperature and ocean water acidity, small changes have large implications. Decreasing oxygen levels in the ocean pose a huge risk to marine ecosystems and, consequently, to humans.

The solubility of gases in water decreases as temperature increases, so warmer water holds less dissolved gas, including oxygen. Approximately 15% of the observed decline in global ocean oxygen content is attributed to warmer ocean temperatures. In addition, as surface ocean water warms, it becomes less dense and less likely to sink and mix with colder, less dense deep water. The overall result is a reduction in physical mixing, which translates to a longer residence time and a decrease in oxygen content of the deep ocean.

Recall from **Chapter 1** (**Figure 1-3**) that the photic zone is the top layer of the ocean where sunlight penetrates. Here, oxygen is produced much faster by photosynthesis than it is consumed by animal respiration and the concentration of dissolved oxygen in the upper few meters of ocean water is saturated for that temperature. Photosynthesis declines rapidly with depth, but respiration continues throughout the ocean, so below the photic zone, the concentration of oxygen decreases continuously as the ocean water flows through the subsurface oceans. Just below the pycnocline is where the water mass has been out of contact with the atmosphere for the longest period of time and where the rate of respiration is high due to the rapid consumption of detritus falling from the photic zone. At this depth, there is an oxygen concentration minimum coinciding with the nutrient maximum.

Currently, large areas of the tropical and subtropical oceans exhibit a strong oxygen minimum zone below the pycnocline (**Figure 16-11**). In these areas, the oxygen minimum zone water has oxygen concentrations below 70 µmol•kg^{-1}, below which marine species (other than those microbial species that are anaerobic) are subject to oxygen deficit stress, so the water is considered to be hypoxic. In smaller areas, where the concentration is essentially zero (anoxic), aerobic marine species can not survive. The volume of both hypoxic and anoxic water has been observed to have expanded during the past five decades. The hypoxic zone has expanded by an area that is more than half the area of the continental U.S., while the area of the anoxic zone has quadrupled. If this trend continues, it will become increasingly more likely that the low oxygen zone will mix upward to affect the upper water layers where there are higher concentrations of marine animal habitats. Recall that for the past few years, hypoxic (concentration of dissolved oxygen low enough to be detrimental to organisms), and at times anoxic (totally depleted of dissolved oxygen), water from this water mass has seasonally moved or been mixed onto the Oregon continental shelf, forming a dead zone (**Chapter 13**).

While the cause of the expansion of oxygen minimum zones is not yet fully known, it has been estimated that about 15% of the total oxygen loss in the oceans is due to the warming-induced reduction in the solubility of oxygen in ocean water. However, warming is responsible for about 50% of the loss in the upper 100 m of the oceans. The remaining 85% of total oxygen loss in the ocean deep waters is likely due to increased stratification, which slows the sinking of oxygen-rich surface water, combined with faster transport of carbon-rich particles to the deep water as primary production increases as a result of nutrient enrichment and warming of the ocean surface layers. It is expected that oxygen in the deeper layers will decline further during the next several hundred years as the deep water is replaced by the meridional overturning circulation, and that this oxygen loss will occur even if there is no continued increase in stratification or nutrient enhancement of primary production. This means that the areas of oxygen minimum zones, in which the oxygen concentra-

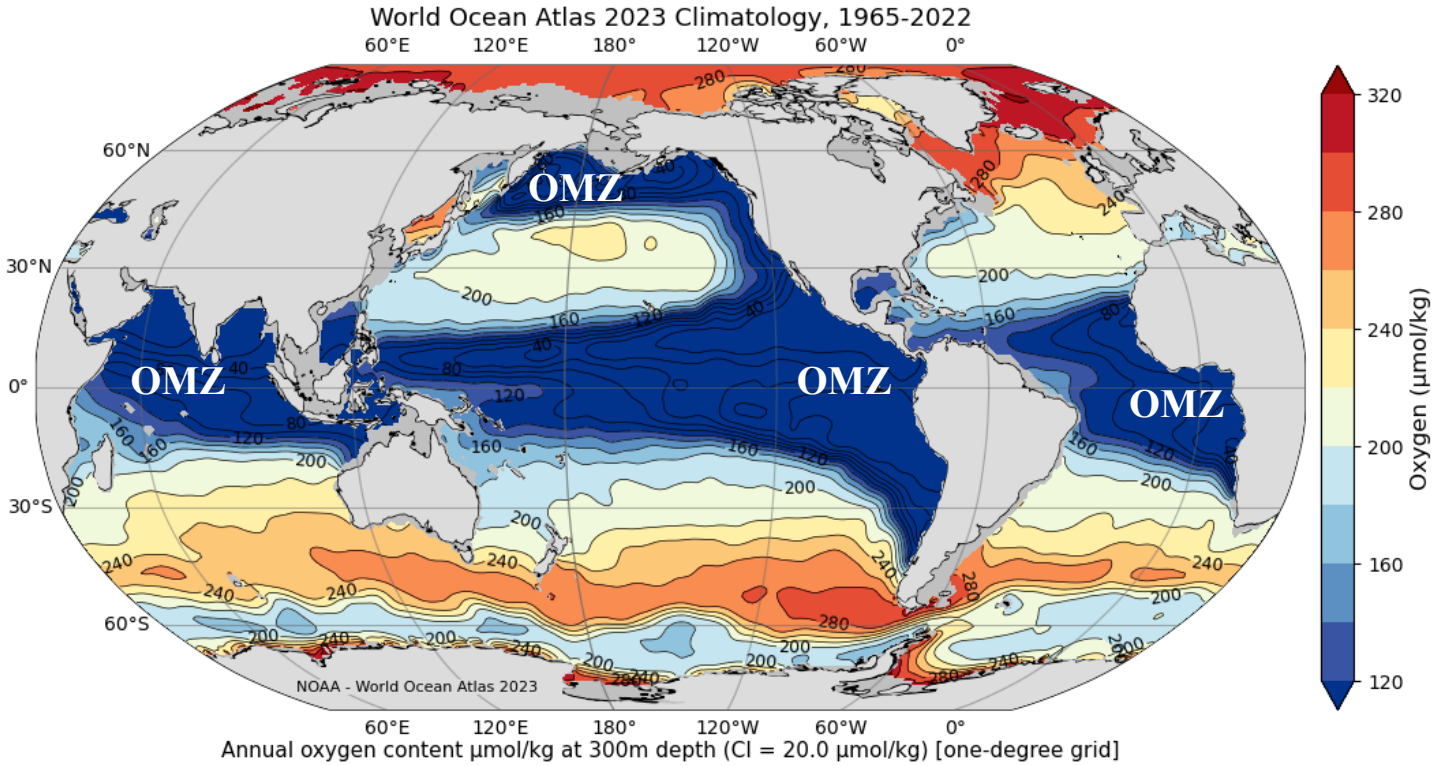


Figure 16-11. The concentration of dissolved oxygen at 300 m depth. This depth is generally below the pycnocline and at approximately the depth where an oxygen minimum occurs. Concentrations in the figure are expressed as µmol•kg^{-1}. The water is considered to be hypoxic at concentrations below 70 µmol•kg^{-1}.

tion is below the concentration needed to support aerobic marine species, will continue to grow for centuries, even if humans were to reduce anthropogenic carbon dioxide and nutrient emissions to zero or near zero immediately.

Recent data and modeling suggest that the post-industrial loss of oxygen concentration now observed in deep ocean waters represents only about 25% of the loss that will occur over the next several hundred years, even if anthropogenic emissions were to be completely stopped immediately. Unless anthropogenic emissions are reduced sufficiently and quickly enough to stop additional warming and further nutrient enrichment of the oceans, the rate at which the oxygen minimum zones will expand will be higher, likely substantially higher, than the now unavoidable rate of increase that will result from the existing warming and solubility loss in surface waters. We are already committed to much expanded deep ocean hypoxic and anoxic zones in the deep oceans with consequent but largely unknown effects on ocean biology and long-term climate. These already committed changes will not be reversed for as much as a thousand years or more even if we immediately stop all anthropogenic greenhouse gas emissions and nutrient releases.

Hypoxia and anoxia have also grown in coastal and estuarine regions during the past 50 years. During this time period, over 500 locations in coastal waters worldwide have been known to experience hypoxia. Fewer than 10% of these ocean areas are known to have experienced any hypoxia before the mid-20th century.

Hypoxic and anoxic water is currently found in only relatively limited areas of the ocean, mostly in the oxygen minimum zones below the pycnocline in the open ocean, and in an increasing number of coastal regions and estuaries where the hypoxia or anoxia is most often caused by inputs of nutrients from sewage and agricultural runoff. However, geologic evidence shows that periods of widespread anoxia within the ocean have occurred throughout Earth's history. Uncertainties remain about the causes of these anoxic events, but they were usually associated with warmer climate conditions, rises in sea level, and occasionally with mass extinctions. For example, global ocean anoxia has been proposed as the main cause for the mass extinction event at the close of the Permian (245 ma).

Climate Change Summary

In summary, while climate change will cause sea-level rise and changes in nutrient supply and ocean circulation that may adversely affect some ocean ecosystems, the more serious global threat to marine life from climate change comes from the combined effects of rising ocean temperature, increased acidity, and decreased oxygen concentration. Given the anticipated range of changes to each of these parameters, many marine species will be stressed or killed, and at least some species will become extinct within the next several decades. Indeed, climate-driven changes in each of these parameters have already been observed to cause harm to marine ecosystems in some parts of the ocean. For example, as discussed above, warming ocean water has caused a rise in the frequency of coral bleaching and damaged coral reef ecosystems. Increased acidity has caused mortality of oyster larvae and reduced reproductive success of pteropods in some parts of the northern ocean. Decreased oxygen concentration has caused episodic dead zones in many parts of the coastal and estuarine ocean and in the deep layers of some ocean areas.

As stated above, deoxygenation has been implicated as a cause of at least one of five mass extinctions in Earth's past and probably at least contributed to the other four mass extinctions. Warming and acidification are thought to have also played a part in these five mass extinctions. Elevated carbon dioxide concentrations in the atmosphere have also been associated with most extinctions. Some scientists have suggested that increased carbon dioxide in the atmosphere drives warming, acidification of the ocean, and deoxygenation of the ocean, and it is the combined effects of these stresses that were responsible for most of Earth's mass extinctions in the past. Moreover, the rate of species extinction has increased in the past few centuries, leading some scientists to hypothesize that Earth may already be experiencing a sixth mass extinction of species.

Much more detailed reliable scientific information on the likely future impacts of climate change, acidification and deoxygenation can be obtained from reports of the Intergovernmental Panel on Climate Change (IPCC).

RISK ASSESSMENT AND MANAGEMENT

None of the issues discussed in this chapter can be totally resolved or avoided without causing environmental and economic impacts. Measures that we might take to reduce the risk of impacts almost always come with unavoidable risks of harm to some other environment or other side effects, and no environmental issue can be solved without economic and social costs. In a world where human civilization exists, it is scientifically impossible to avoid all adverse impacts on all ecosystems. Thus, good stewardship of the Earth requires that we seek ways to minimize the root causes of degradation of global natural ecosystems rather than try to eliminate impacts or risk from any one particular cause among the many discussed in this chapter. The scientific way to minimize the total impacts of humans on the environment is through risk assessment and management, focused on prioritizing the reduction of the highest risk impacts.

Risk-based Earth stewardship is not simple nor easy, since risk itself is composed of several elements, and each element is very difficult to adequately assess and assign a value to. The two primary elements of risk are, first, the probability that an undesirable outcome will occur without corrective action, and, second, the severity of the outcome if corrective action is not taken before the outcome occurs. Further complications exist because the public perception of risk cannot be ignored and is often not based on either of the factors mentioned in the previous sentence. For example, the risk of a significant oil spill from an offshore oil rig is extremely small, many orders of magnitude less than the chance that numerous humans will be killed in auto accidents in a single day. Also, the effects of even the largest spill from any offshore oil rig, while dramatic and certainly undesirable, are limited to the region local to the spill, and are temporary (adverse effects disappear within a few years or so - a blink of the eye in geological time). Nevertheless, the public perception is that this risk should be avoided at any cost.

Although quantitative risk assessment is difficult, qualitative assessment of risks using the two primary risk elements can be useful. For example, all of the risks discussed in this chapter are considered highly likely to occur. However, with the exception of climate change/acidification/deoxygenation, all the issues discussed in the chapter would impose adverse impacts only in limited areas of the oceans and for geologically short time periods. Climate change, acidification, and deoxygenation are also likely

to occur, but we have less certainty that their worst-feared effects will occur. However, the potential global consequences of climate change/acidification/deoxygenation set this issue aside from all others discussed in this chapter, since the consequences of not taking action could result in global mass extinctions, and severe damage to human food supply and the infrastructure that supports human civilization. Human civilization, and even the survival of the human species, are also within the scope of possible risk consequences. These adverse effects might take centuries to fully develop, but they would be geologically long-lasting events.

A reasonable assessment of ocean pollution priorities, based on what we know about the effects and risks associated with each area of concern discussed in this chapter, is that climate change/acidification/deoxygenation is by far the dominant ocean pollution issue and that carbon dioxide and nutrients, principally nitrogen, are the most harmful ocean contaminants.

CHAPTER SUMMARY

Assimilative Capacity.

The oceans can safely assimilate wastes if the rate at which the waste is introduced does not exceed the assimilative capacity, which is the point at which toxic or other adverse effects occur. Assimilative capacity varies by waste and location because residence time determines the concentration of contaminants, and each contaminant has a different concentration–effect relationship. Release of a specific type and amount of contaminant that causes pollution in one location may not do so elsewhere.

Adverse Effects of Human Activities.

Increased turbidity can reduce primary productivity. Excessive nutrient inputs can alter phytoplankton species composition and can cause blooms, eutrophication, and hypoxic or anoxic bottom waters.

Habitat can be altered by development and by discharges of wastes. Many areas of mangrove swamps and coastal wetlands have been filled and developed. Damming of rivers has prevented or inhibited anadromous and catadromous fish migrations and has altered salinity regimes and circulation in estuaries. Dredging, anchoring, fishing, and other activities disturb and alter seafloor habitats.

Community structures within ocean ecosystems can be altered when human activities affect habitat or affect some species but not others. Selective harvesting of fish, invertebrates, and marine mammal species has caused major changes in communities in some areas.

Toxic substances released to the oceans can be concentrated in seafood and present a human health risk or result in economic loss if the resource is unfit to eat. Contamination of seafood, particularly shellfish, has caused many shellfisheries to be closed and sometimes has caused human disease outbreaks.

Coasts have been marred and altered in many locations by structures. Many beaches are periodically closed because of contamination with improperly treated sewage or medical wastes.

Toxicity.

With the possible exception of carcinogens, teratogens, and mutagens, toxic substances are toxic only above a critical concentration that varies by substance, species, and even life stage within a species. The toxicity of a waste can be evaluated by comparing contaminated sites with control sites or by performing laboratory bioassays. Both approaches are difficult, and their results must be carefully interpreted. Many toxic substances are bioaccumulated by most species. Certain toxic substances are biomagnified, so their concentration increases at each trophic level.

Petroleum.

Natural inputs from seeps are the largest source of most oil released to the oceans. Stormwater runoff and other discharges from the everyday uses of petroleum are also a very large source. Oil tanker accidents are a far smaller source, and releases from offshore platforms are even smaller.

When oil is spilled, a slick forms and the volatile compounds evaporate to the atmosphere or dissolve, leaving lumps of tar or, if seas are rough, a gummy suspension called “chocolate mousse.” If the slick reaches shore, oil coats any substrate but is eventually decomposed by bacteria.

Oil spill events damage the ecology of shores reached by the oil and kill seabirds and marine mammals in the spill area. Some damaged areas recover naturally within a few years. Wetlands and other low-energy coastal habitats recover more slowly than high-energy rocky shores or beaches. Some spill cleanup efforts may have little or no benefit and may even retard natural recovery. Long-term effects may persist in some spill areas, but they are difficult to detect and document.

Sewage.

Sewage is discharged to the marine environment to protect public health. Sewage is a natural material, composed mostly of water and particulate and dissolved organic matter that is contaminated with chemicals from household wastes and industry. Sewage also contains pathogens that can be classified as pollution because the pathogens can infect humans through water contact or seafood consumption. Organic matter and nutrients, especially nitrogen, can cause algal blooms and anoxia, and toxic compounds can accumulate in discharge-area ecosystems. Sewage treatment removes floatables, particulates, and some dissolved organic matter, pathogens, and some potentially toxic chemicals. Treatment has substantially reduced the incidence of anoxia in rivers and estuaries.

Particulate organic matter from sewage outfalls can accumulate in sediments around the outfall and cause alteration of benthic infaunal communities. If outfalls discharge large amounts of sewage, the benthic infauna is degraded in a zone around the outfall, but the effects decrease with distance. If the same amount of sewage were discharged from several small outfalls instead of a single large one, no areas would be degraded, and the benthic infauna around each outfall would be enhanced.

Urban and Agricultural Runoff.

Runoff from streets and agricultural land contains toxic chemicals, nutrients, particles from paints, solvents, oil, and other substances deposited by vehicles, combustion products, pesticides, fertilizers, and many other sources. In estuaries, these nonpoint source inputs are often much larger than sewage or industrial inputs.

Industrial Effluents.

Industrial discharges of toxic substances and other contaminants have been considerably reduced in recent decades. However, violations of regulations and illegal discharges to sewers and streams are common. The industrial effluents of a chemical company in Minamata, Japan, in the 1950s caused the only documented case of human deaths due to toxic substances (methylmercury) discharged to the marine environment. DDT

discharges have caused ecological damage in a number of coastal ocean areas.

Dredged Material.

Navigation channels that are dredged to maintain navigation depths are often sites of accumulation of past and present contamination. Dredging damages the benthos at the dredging site and at the dump site, which is usually nearby in the estuary or coastal ocean. Toxic contaminants in dredged material are preferentially released to the suspended sediment during dumping and may be bioavailable. Most of the fine-grained, contaminant-rich dredged material dumped in estuaries or just outside estuary mouths is transported back into the estuary by the estuarine circulation and may accumulate in channels to be dredged again.

Plastics and Trash.

Trash, particularly floating trash, is dumped into rivers and the ocean and can cause aesthetic problems when washed up on beaches or accumulated in areas visited by divers. Plastics are a problem because they degrade very slowly, and they may strangle or choke birds and marine organisms or accumulate in the gut until the animals starve to death.

Antifouling Paints.

To be effective, antifouling paints must be toxic and must be slowly released to solution. Tributyltin, used in some paints, is very persistent and highly toxic. It has accumulated in some estuaries to toxic levels, drastically reducing populations of commercially valuable shellfish and other invertebrates.

Radionuclides.

The oceans have been contaminated by radionuclides from testing of nuclear weapons, liquid waste discharges, and dumping of radioactive wastes. Other than at a few nuclear bomb test sites, radionuclide concentrations in the oceans do not present a significant human health or ecological risk. However, the former Soviet Union disposed of nuclear submarine reactors and large quantities of radioactive wastes in the Arctic Ocean and the Sea of Japan, and there is concern that these materials may eventually release radionuclides to the food web.

Noise.

The oceans are filled with numerous sources of natural sound. However, additional noise is contributed by ships, resource extraction activities, and military and civilian use of sonar. Intense sounds at certain frequencies have been found to be harmful to marine mammals. As a result, there is considerable concern that the increased anthropogenic sound in the oceans may cause harm to marine species.

Nonindigenous Species.

Species are carried in ships, in ballast water, and attached to hulls and are inadvertently introduced to ecosystems where they do not occur naturally. Species are also deliberately introduced. Many introduced species do not thrive, but some outcompete important species in their new habitat and may totally disrupt natural food webs. Estuaries have been particularly severely damaged by nonindigenous species.

Habitat Alteration.

Alteration or destruction of habitat, especially filling of wetlands, is among the most damaging forms of pollution, especially in estuaries and the coastal zone. Habitat can also be altered in many other ways, such as by dredging, by the construction of structures that affect circulation and erosion, and by the reduction of river flow rates that results from the withdrawal of freshwater for human uses.

Fishing.

Many ocean fisheries, perhaps most, are overfished. Many fish stocks have collapsed due to overfishing, and some do not recover even if the fishing pressure is relieved. Fishing also contributes to ocean pollution in many other ways, especially through loss of fishing equipment, much of which is now made of synthetic materials that are highly resistant to decomposition, and bottom trawling that destroys benthic habitat.

Climate Change.

Global climate change has caused the oceans to warm. The warming has caused changes in a number of ocean processes that have resulted in adverse impacts on marine ecosystems and humans, some of which are likely to become greater and many of which will continue to drive change in the oceans for centuries to come. Impacts include changes in ocean circulation and evaporation/precipitation patterns; increases in wave and storm energy affecting coastlines; melting of sea ice and glaciers; rising sea level; and impacts on marine biological systems, including coral bleaching due to warmer water. The rate of change of ocean temperature, acidity, oxygen levels, and other ocean conditions due to climate change is faster than has occurred at any time in Earth's recent history, and these changes are expected to result in species extinctions and continuing disruption of marine species life cycles and distribution.

Acidification.

Anthropogenic releases of carbon dioxide cause carbon dioxide to be taken up by seawater, where a series of chemical reactions causes the acidity of ocean water to rise. Adverse effects of elevated acidity have already been observed in several areas of the world's oceans involving a variety of marine species. Most at risk are coral reefs and marine species that use calcium carbonate to construct their skeletal material, such as oysters and pteropods.

Deoxygenation.

Elevated ocean temperatures due to climate change have reduced the solubility of oxygen and, therefore, the concentration of dissolved oxygen in ocean waters. Lower oxygen concentrations in water sinking to form deep ocean waters, together with changes to stratification and primary production caused by anthropogenic releases of carbon dioxide and nutrients, especially nitrogen, have expanded the area of open ocean oxygen minimum zones in which hypoxia and anoxia are present. Upwelling has caused some of this water to be transported onto the continental shelf off Oregon, killing marine species and causing what is known as a dead zone. Similar processes have also led to the development of hypoxia and anoxia in more than 500 coastal areas that have resulted in dead zones and the deaths of marine organisms that are unable to avoid these zones.

Climate Change Summary.

The release of anthropogenic carbon dioxide, together with anthropogenic releases of nutrients, especially nitrogen, causes multiple impacts on the oceans. These impacts include sea level rise, loss of sea ice, coral bleaching, ocean acidification, and deoxygenation due to the warming of ocean water. These anthropogenic releases also cause changes in ocean stratification and primary production that also cause deoxygenation. The combination of elevated carbon dioxide in the atmosphere, warming and acidification of ocean water, and deoxygenation of the oceans has

been associated with at least some of Earth's five mass extinctions.

Risk Assessment and Management.

Scientific risk assessment must consider both the probability that a feared impact might occur and the severity of the impacts if they do occur. The consequences of climate change/acidification/deoxygenation could include mass extinctions and other global and long-lasting environmental and economic impacts. These potential consequences make this the most important ocean pollution issue.

KEY TERMS

You should be able to recognize and understand the meaning of all terms that are in boldface type in the text. All of those terms are defined in the Glossary. The following are some less familiar key scientific terms that are used in this chapter and that are essential to know and be able to use in classroom discussions or on exams.

anadromous
anoxic
anthropogenic
assimilative capacity
beaches
benthic algae
bioaccumulation
bioassays
bioavailable
biochemical
biogeochemical cycles
biomagnification
biomass
bloom
brackish
bulkheads
carcinogens
catadromous
coastal zone
community
complexes
contaminant
continental shelf
currents
DDT
decomposers
diffuses
diversity
DNA
ecosystems
effluent
embryo
environment
eroded
estuaries
eutrophication
friction
genetic
grain size
grazing
groundwater
habitat
hypoxia
invertebrates
isotopes
jellies
latitudes
limiting nutrient
macroalgae
mangrove
microalgae
mollusks
mutagens
nonindigenous species
nutrients
outfalls
overfishing
oxygen-demanding
pathogens
PCBs
pelagic
photic-zone
photosynthesis
phytoplankton
plate tectonics
pollution
primary production
radioactivity
radioisotopes
reef
residence time
respiration
resuspend
salinity
saturation solubility
sea grass
sediment
sedimentation
sedimentation rate
shellfish
shore
shoreline
spawning
species
suspended sediment
teratogens
topographic
tracers
trophic levels
turbidity
virus
wetlands

STUDY QUESTION

1. What is the difference between contamination and pollution?
2. Explain assimilative capacity. How are assimilative capacity and residence time linked?
3. How can human activities alter primary production?
4. Which human activities cause alterations in marine habitats? How many can you list? In what way do each of these activities alter habitat?
5. How can we evaluate the toxicity of a substance to marine species? Why is it so difficult to decide what concentration is safe in the environment?
6. What is the difference between bioaccumulation and biomagnification? Why should we be more concerned about toxic substances that are biomagnified?
7. In what ways can fishing damage the marine ecosystem?
8. List the principal sources of contamination in the oceans. Summarize the characteristics of each type of waste or other source
9. What are antifouling paints? What would be the desirable characteristics of a future antifouling paint?

CRITICAL THINKING QUESTIONS

1. What is the difference between naturally occurring toxic substances and synthetic toxic substances that suggests that they might be considered differently by policy makers and managers concerned with marine pollution?
   (a) Do you think discharges of these two types of substances should be subject to different rules? Why or why not?
   (b) Do you think the production of all synthetic toxic substances (without any exception) should be banned?
   (c) If only some such substances are to be banned from being produced while others are allowed to be produced but their discharges regulated, what factors would you consider in deciding which of these two policies should be applied to a specific synthetic toxic substance?
2. In this chapter, it is speculated that the use of oceans for sewage waste disposal was one of the most effective advancements in human health protection in history. Do you think this statement is correct? Why or why not?
3. DDT has been banned from production and use in many countries, primarily in mid-latitudes, where it was previously used on crops for insect control. However, DDT is still produced and used in large amounts in some nations, particularly developing nations in tropical regions where malaria is rampant. Although effective substitutes for DDT exist, they are not used in these countries, because they cost too much. What should be done about this situation, and how?
4. On an annual average, petroleum hydrocarbons from street runoff contribute more than twice the volume of oil spilled in the oceans from tanker accidents.
   (a) What are the sources of petroleum hydrocarbons in street runoff?
   (b) What would you suggest politicians do to reduce the amount of petroleum hydrocarbons released to bays and estuaries by this route?
   (c) Should politicians require all storm water runoff to be

treated to remove the hydrocarbons?
(d) Should politicians attempt to control the release of hydrocarbons to the environment so that they do not get into the storm water? How could this be done?
(e) What can you personally do to reduce the amount of hydrocarbons that you release to the environment?

5. Describe the principal sources of petroleum contamination in the oceans. Discuss what would probably cause more pollution of the oceans: production of oil from drilling platforms in U.S. coastal waters and transport of the oil ashore in seafloor pipelines, or purchase of oil from foreign suppliers and transport to the United States in oil tankers.
6. Because of environmental concerns, offshore oil exploration is currently banned in large areas of the Pacific and Atlantic continental shelves of the United States, despite the successful safety record of the oil industry operating under U.S. laws and regulations. Some oil companies are drilling instead in other areas, such as the ice-filled waters near the Russian island of Sakhalin, where the safety and environmental rules are weaker and sometimes totally unenforced, and from where the oil must be transported long distances to the locations where it is used.
(a) Discuss the implications that drilling operations like the one conducted off Sakhalin Island might have for the ocean environment as a whole.
(b) Should the drilling bans in U.S. waters be continued? Describe all the reasons for your answer.
(c) If the ultimate political decision were to increase the drilling and oil activity in U.S. waters, what studies should be done or actions taken before such drilling took place?
(d) Have such studies been done already?
7. Describe the principal adverse effects of sewage discharged to the oceans and how they can be reduced or eliminated. What actions have been taken to reduce or eliminate sewage pollution of the oceans in the United States? Have these actions been effective?
8. Billions of dollars have been spent on the construction of secondary sewage treatment plants in all cities and towns regardless of the locations of their discharges.
(a) Was this uniform approach justified scientifically? If so, why? If not, what other approaches to sewage treatment and disposal might have been taken?
(b) What are the characteristics of sewage that you would wish to modify by alternative treatment approaches before discharging it to the oceans?
(c) What are the factors that you would consider in deciding where you might not require secondary treatment or where you might allow only primary treatment?
(d) How would you determine the environmental benefits or detriments of alternative treatments?
9. Numerous sources release trace metals, toxic organic substances, nutrients, and pathogenic microorganisms to the environment. These releases are eventually discharged to the oceans in sewage, urban storm-drain runoff, and runoff from agricultural land.
(a) List as many of these sources as possible.
(b) What substances do the various sources contain
10. After you have answered Critical Thinking Question 9 above, take a look at the labels on all of the containers of cleaning fluids and powders, cosmetics, shampoos, paints, and other materials around your house.
(a) What additional sources can you now list?
(b) Where do these products and their chemical constituents go after you have used them?
(c) Make two lists: one of the products whose containers tell you enough about their composition for you to decide what contaminants they might release to the environment, and another of those that do not. Do you know what is in the products that do not tell you on their label what they contain?
(d) Why do some products have information on their labels that divulge their composition, while other products do not? Should this situation be changed? If so, how?
11. Discuss why it is more difficult to control contamination of the oceans from urban and agricultural inputs than from industrial inputs.

CRITICAL CONCEPTS REMINDERS

CC8 Residence Time: The residence time of seawater in a given segment of the oceans is the average length of time the water spends in that segment. The residence times of some coastal water masses are long, therefore some contaminants discharged to the coastal ocean can accumulate to higher levels in these long residence time regions than in areas with shorter residence times.

CC14 Phototrophy, Light, and Nutrients: Phototrophy (which includes photosynthesis) is the primary process by which simple chemical compounds are made into the organic compounds of living organisms. Photosynthesis depends on the availability of carbon dioxide, light, and certain dissolved nutrient elements including nitrogen, phosphorus, and iron. Alterations of the availability of any of these elements by human activity can have adverse consequences in marine ecosystems.

CC17 Species Diversity and Biodiversity: Biodiversity is an expression of the range of genetic diversity; species diversity; diversity in ecological niches and types of communities of organisms (ecosystem diversity); and diversity of feeding, reproduction, and predator avoidance strategies (physiological diversity), within the ecosystem of the specified region. Species diversity is a more precisely defined term and is a measure of the species richness (number of species) and species evenness (extent to which the community has balanced populations with no dominant species). High diversity and biodiversity are generally associated with ecosystems that are resistant to change. Changes in diversity are often used as an indicator of the impacts of human activities.

CC18 Toxicity: Many dissolved constituents of seawater become toxic to marine life at levels above their natural concentrations in seawater. Some synthetic organic chemicals are especially significant because they are persistent and may be bioaccumulated or biomagnified.

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Figure 16-3 – Segar, D., and E. Stamman Segar, 1997: Sugar cane fields burned after harvest to clear the land for new planting in Hawaii.

Figure 16-4a – Segar, D., and E. Stamman Segar, 1997: The Moss

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Figure 16-4c – Segar, D., and E. Stamman Segar, 1997: A marina at Antioch, California, constructed on a former wetland in the San Francisco Bay delta.

Figure 16-5a – Segar, D., and E. Stamman Segar, 1997: The *Exxon Valdez* tanker 48 h after it ran aground on Bligh Reef in Prince William Sound, Alaska, in 1989.

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Figure 16-7a – Adapted from Smith, W. E., and A. M. Smith, 1975: *Minamata: The story of the poisoning of a city, and of the people who choose to carry the burden of courage*. Holt, Rinehart, and Winston, 192 pp.

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Figure 16-8b – Segar, D., and E. Stamman Segar, 1997: The Alcatraz dredged-material dump site in San Francisco Bay.

Figure 16-9a – NFWS, 1985: Northern fur seal entangled in netting. NOAA.

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