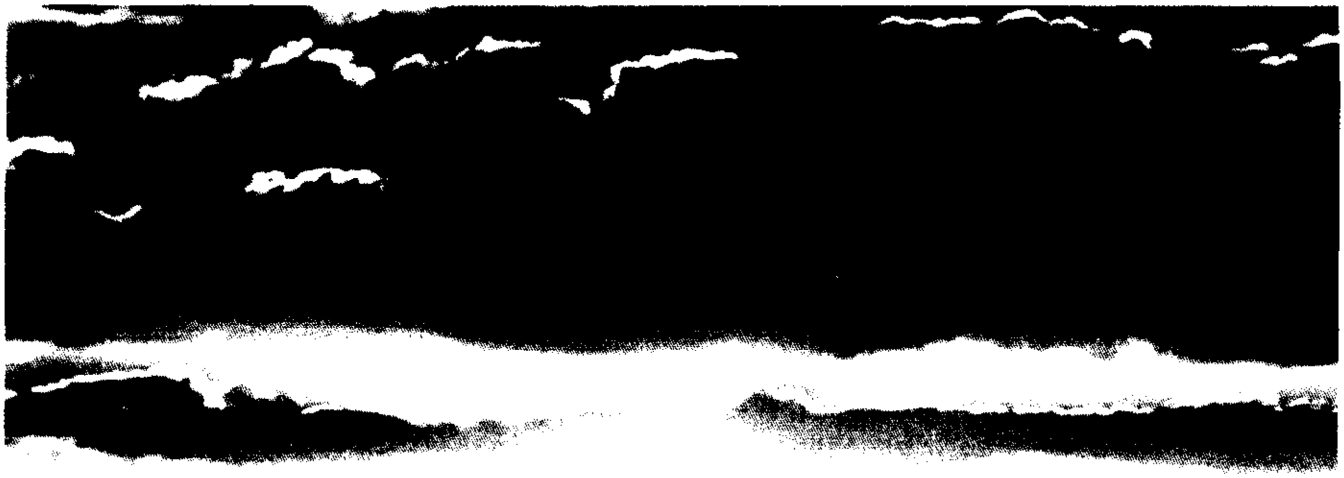

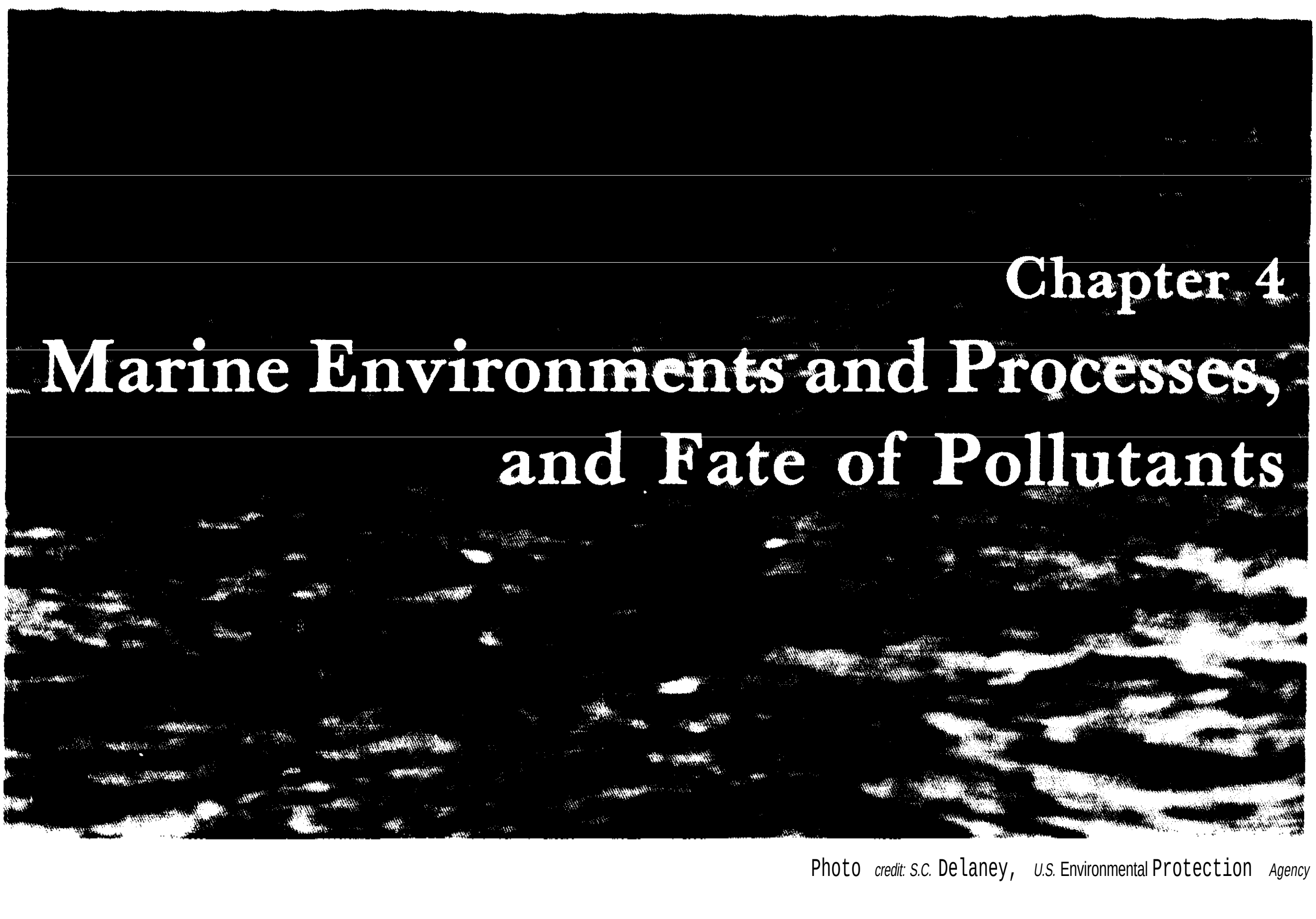

Chapter 4
Marine Environments and Processes, and Fate of Pollutants

Photo credit: S.C. Delaney, U.S. Environmental Protection Agency

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Chapter 4

Marine Environments and Processes, and Fate of Pollutants

Marine waters are classified in this report into three categories: estuaries, coastal waters, and the open ocean.[1] The multitudes of different organisms that inhabit these waters require certain environmental conditions to survive and reproduce (box K). Changes in these conditions can occur as a result of waste disposal activities, depending on the fate of the wastes and associated pollutants and on the susceptibility of the waters and organisms to impacts.

The fate of wastes and associated pollutants, and the susceptibility of organisms to impacts from these substances, is influenced by features of marine environments and the organisms. For example, wastes and associated pollutants generally are dispersed and diluted by physical processes that transport and mix water; these physical processes, however, vary greatly in relation to a waterbody's degree of enclosure, currents, volume, and depth. In contrast, the concentrations of some pollutants can increase after disposal because of chemical processes (e. g., adsorption of pollutants to solid material), physical features (e. g., salinity gradients), or biological processes (e. g., the ability of organisms to accumulate some pollutants),

The three marine environments differ in their general susceptibility to adverse impacts. To understand how the various marine environments are affected by wastes, it is important to consider three issues: 1) the fate of wastes and associated pollutants after disposal, 2) the relationships between pollutants and specific impacts, and 3) whether marine environments can assimilate wastes or recover from adverse impacts,

[1]Some water-bodies may exhibit a combination of characteristics.

TYPES OF MARINE ENVIRONMENTS AND THEIR SUSCEPTIBILITY TO ADVERSE IMPACTS

Estuaries

An estuary is a semi-enclosed waterbody with a free, but often small, connection to coastal waters or the open ocean, within which seawater is measurably diluted with freshwater from land drainage (fig. 8; ref. 612). Estuaries can vary greatly in size, shape, and degree of freshwater influence. For example, the category includes tidal marshes and lagoons, as well as the mouths of large rivers such as the Connecticut and Mississippi rivers. The Chesapeake Bay is considered an estuary because it is semi-enclosed and influenced by several rivers (including the Susquehanna and Potomac rivers).

Estuaries are among the most ecologically and economically important of all aquatic environments. Their productivity is generally very high because nutrients are plentiful (figure 9); large quantities of nutrients stimulate growth, reproduction, and photosynthesis in phytoplankton, and large populations of phytoplankton support large populations of other organisms. The nutrients are generally the result of discharges and runoff from the land, which tend to get trapped when they enter estuaries. Many marine organisms, including some that live primarily in coastal or open ocean waters and some that are very important commercially, migrate into and use estuaries during critical parts of their life cycles. For example, estuaries provide critical breeding, spawning, and nursery habitat for many fish and shellfish, and they also provide important habitat for many birds and mammals; some of these organisms (e. g., bald eagles and several types of whales) are endangered species. The submerged aquatic vegetation (SAV) in estuaries, such as seagrass beds or kelp forests, is important ecologically as a source of food and shelter for many organisms and in stabilizing sediments.

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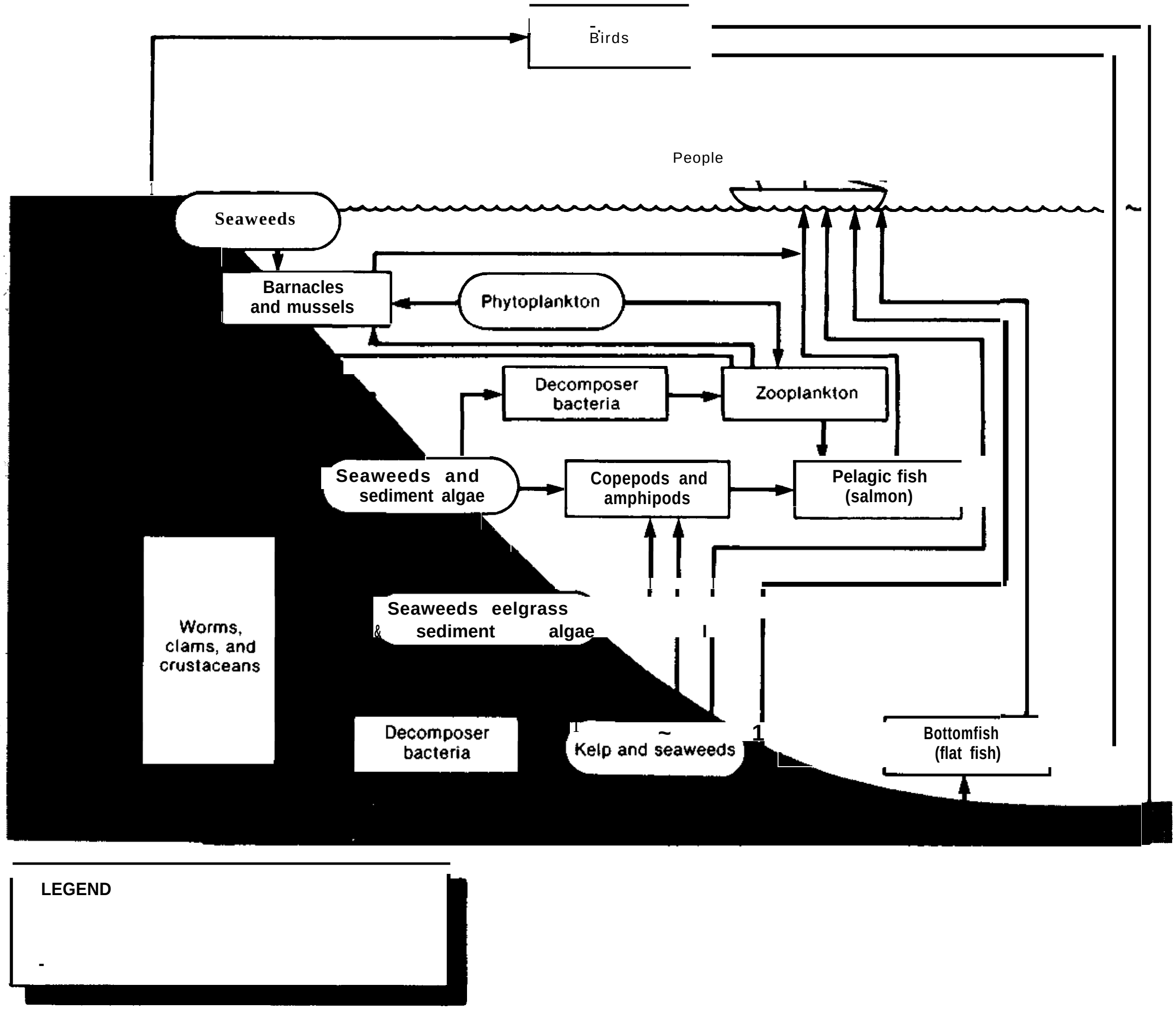
Figure 7.-Generalized Marine Food Web

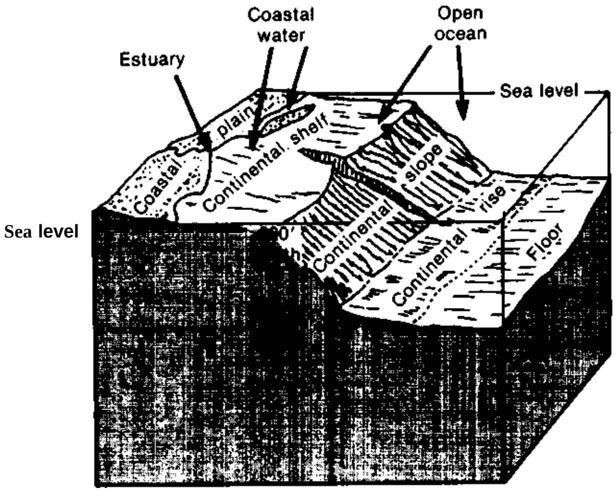


SOURCE: Puget Sound Water Quality Authority, *The State of the Sound 1986* (Seattle, WA: July 1986).

Estuarine circulation systems can be extremely complex and variable, depending on freshwater flow, tidal action, wind, depth, and shape (100). Tidal action and seasonal circulation patterns, for example, transport and mix freshwater and saltwater to varying degrees. Freshwater is lighter than seawater, so it tends to flow into estuaries along the surface, while seawater tends to enter below it.

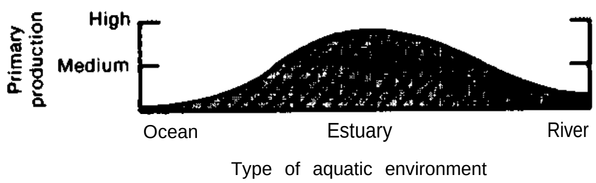
It is useful to distinguish three types of estuaries based on the degree of mixing or stratification of freshwater and saltwater (165): 1) highly stratified (or salt-wedge) estuaries (figure 10), exemplified by the mouth of the Mississippi River; 2) partially mixed estuaries such as the James River estuary in Virginia and the Chesapeake Bay; and 3) well-mixed or homogeneous estuaries, which are rare but do illustrate an extreme in mixing and stratification patterns. The stratification of the water column creates water layers of different densities, with pycnoclines marking the layers. During the course of a year, a single estuary may exhibit a

Figure 8.—Types of Marine Environments



SOURCE A.W Reed, *Ocean Waste Disposal Practices* (Park Ridge, NJ: Noyes Data Corp., 1975)

Figure 9.— Primary Productivity In and Near a Typical Estuary



Primary productivity represents the amount of organic material produced by photosynthesis. The peak in primary productivity typically occurs in estuaries; as a result, estuaries contain abundant food resources and serve as nursery areas for many species (including some saltwater and freshwater organisms that move into estuaries during the breeding portion of their life cycle).

SOURCE J R Clark, *Coastal Ecosystem Management' A Technical Manual for the Conservation of Coastal Zone Resources (New* York, NY: John Wiley & Sons, 1977)

range of mixing or stratification, which means that organisms inhabiting it must be capable of tolerating large changes in environmental conditions.

Estuaries and the organisms using them are highly susceptible to adverse impacts. One reason for this is that many organisms use these waters during particularly critical periods of their lives. Second, estuaries often trap particulate matter and nutrients that enter them via rivers, runoff, and waste disposal (effluent discharge or dumping). These waters bear the brunt of marine disposal activities.

Trapping varies among estuaries. In stratified or partially stratified estuaries, material begins to

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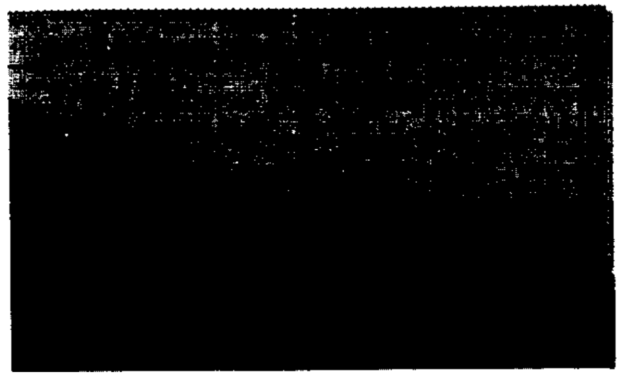

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and then is carried back toward the upper portion of an estuary by the landward-flowing saltwater. This happens in the upper Chesapeake-Bay, where most of the sediment carried by the Susquehanna River is trapped (139). In shallow or relatively unstratified estuaries, particles can descend quickly to the seafloor, where they are less subject to physical processes that might flush them from the estuary.[2] Particles also descend more quickly when they stick together and increase in size and density, a process called ***flocculation*** which is enhanced when freshwater mixes with saltwater. Well-mixed estuaries generally trap less particulate matter because they are more subject to physical processes that can flush water from an estuary. In addition, flooding in the watershed of a small estuary may reduce trapping because the high influx of freshwater transports most particles to the sea (349).

In most estuaries, trapping plays an important role in determining the fate of pollutants and the likelihood of impacts. For example, although nutrients can stimulate productivity, trapping of nutrients can lead to nutrient enrichment (eutrophication), which can result in low levels of dissolved oxygen. In addition, many metals, organic chemicals, and pathogens bind to the surfaces of particulate material (e. g., suspended solids) and thus are frequently trapped in estuaries. These pollutants can cause problems when they are ingested by

[2] The rate at which water in an estuary is replaced is called the flushing rate.

organisms, and the problems can be magnified when the y are passed up the food chain to other organisms, including humans. If inputs of toxic pollutants are frequent or large enough, "hot spots" of contaminated sediments such as those in San Francisco Bay can occur (395).

Estuaries and estuarine organisms can recover from certain impacts if the inputs of pollutants are reduced or terminated. For example, some water quality impacts such as low dissolved oxygen levels or eutrophication can be reversed; similarly, areas where populations or communities have been destroyed by physical burial can be recolonized if individuals of the same species are capable of migrating back into the areas. Other impacts, however, may require more time to be reversed or may in some cases be irreversible. For example, contamination of sediments with metals or persistent organic chemicals or major changes in community structure can be impossible to correct.

Coastal Waters

Coastal waters include those waterbodies lying over the inner portion of the continental shelf that are less enclosed and more saline than estuaries; these waters generally, but not always, lie within 3 miles of shore (i. e., within the boundary of the territorial sea) (figure 8). The movement of water and material in coastal waters is heavily influenced by tidal action and wind, as well as oceanic forces such as longshore currents, coastal upwelling of bottom waters, eddies, and riptides (99). Rivers may influence these waters to some degree, but this effect is generally less than in estuaries.

Coastal waters also vary greatly in shape, size, and configuration. They include bays (e. g., Mon-

B

terey Bay), sounds (e. g., Puget Sound), and open waters along the shoreline (e. g., the Southern California Bight). The New York Bight is considered a coastal water, even though it extends beyond the 3-mile boundary, because it is located on the inner edge of the continental shelf and is heavily influenced by river drainage.

Coastal waters tend to be moderately productive, although less so than estuaries because they receive fewer nutrients; some coastal waters such as Monterey Canyon off of central California are extremely productive. Again, submerged aquatic vegetation provides food and shelter for many organisms. As a result, coastal waters also tend to be ecologically and economically important, and often contain important fishing grounds that can be affected by pollutants from waste disposal activities. Many organisms that normally inhabit coastal waters migrate into estuaries and rivers during portions of their lives (e. g., for spawning). In addition, some endangered birds and mammals migrate through and use coastal waters, primarily to obtain food.

In comparison with estuaries, coastal waters are more directly linked to the open ocean and tend to disperse and dilute pollutants somewhat more readily. Trapping is less important than in estuaries, but it can be significant in small inlets and embayments (e. g., in Puget Sound where several toxic "hot spots" have developed). In addition, coastal currents can transport pollutants toward or along the shoreline instead of out to sea. These pollutants can accumulate in organisms and sometimes be transferred to other organisms in the food chain.

Coastal waters can recover from impacts such as eutrophication and hypoxia if the problem inputs are reduced or terminated. In many cases, the more open and dispersive coastal waters (relative to estuarine waters) restrict buildups of excess nutrients or bring in waters with higher oxygen levels. On the other hand, seasonal pycnoclines and thermoclines are typical of many coastal waters, and these features can contribute to increased eutrophication and hypoxia, at least temporarily. Some impacts, such as contamination of sediments with toxic pollutants, can be difficult or impossible to reverse.

The Open Ocean

The open ocean refers to waters overlying the outer portion of the continental shelf, the continental slope, and beyond (figure 8); together, these waters comprise about 92 percent of the Earth's surface water. Open ocean waters are deeper, more open, and more saline than coastal waters and estuaries. In comparison with estuaries and coastal waters, the open ocean is influenced less by tidal flow and more by permanent ocean currents. Open ocean processes are more capable of dispersing and diluting wastes and associated pollutants.

The open ocean typically is not as biologically productive as are estuaries and coastal waters, primarily because of a general lack of nutrients. An exception to this occurs in localized areas of upwelling, where nutrients and oxygen are transported up to surface waters, for example in the Georges Bank off the New England coast. This increase in nutrients can result in increased productivity of phytoplankton and corresponding increases in local fish populations. As a result, resources in the open ocean can be commercially important even though they are distributed unevenly (i. e., concentrated in certain areas and relatively absent in others). Many open ocean organisms, particularly some fish and mammals, also migrate to and spend portions of their life cycles in estuaries and coastal waters.

The open ocean is generally less vulnerable than other marine waters to many impacts because of its large volume and free exchange of water; open ocean currents generally have a considerable capacity to transport, disperse, and dilute wastes or pollutants. As a result, problems such as hypoxia and eutrophication (which generally occur only when certain conventional pollutants and nutrients are present in high concentrations) and physical burial of organisms are less likely to occur.

However, some metals, organic chemicals, and pathogens are of concern, even though they also are dispersed, because they can: 1) cause impacts at low concentrations, 2) persist in the environment, 3) accumulate in organisms, and 4) increase in concentration in successive levels of marine food chains. Some of these pollutants have been detected in significant concentrations in the water and in the tissues of fish, seabirds, and marine mammals. The significance of such contamination, and whether organisms and populations can recover from associated effects, is not always clear because of insufficient knowledge in several areas. For instance, questions remain about: how open ocean food chains operate, what concentrations of chemicals cause reproductive failure in marine organisms, how tolerant open ocean organisms are to change, and the likelihood of pollutants being transferred to humans. In addition, detection of such impacts is difficult and the impacts may not be observed until long after the polluting incident is over.

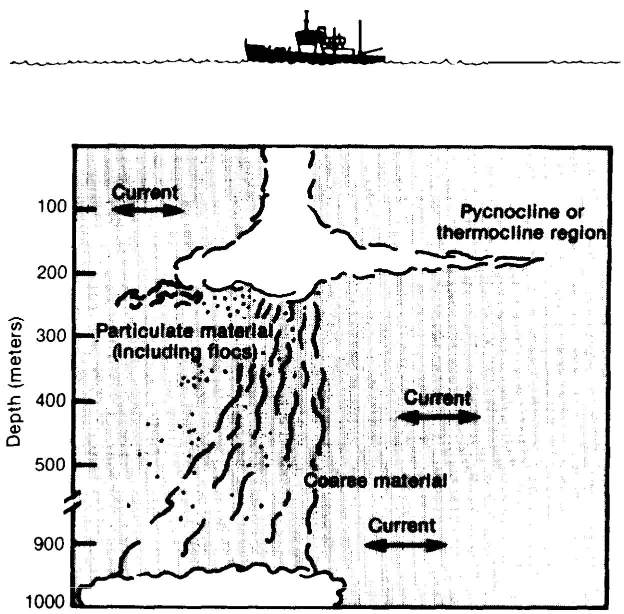
FATE AND DISTRIBUTION OF WASTES AND ASSOCIATED POLLUTANTS

The ultimate fate of wastes and associated pollutants depends to a large extent on the many different processes that affect dispersion and deposition. Initially, wastes are diluted immediately after entering the water. Simultaneously, other processes begin to transport wastes and pollutants over longer distances and over time to modify their chemical and biological nature. Besides initial dilution, waste particles and pollutants are affected by: 1) physical transport (e. g., transport as part of a water mass, whether they are suspended or dissolved in the water); 2) biological transport[3] (e. g., extraction by plants and animals and subsequent movement with the organisms or their remains or excretions); and 3) sedimentation (e. g., attachment to clays and organic materials as they settle through the water column and eventual incorporation into bottom sediments) (262). Figures 11 and 12 depict the general fate of dumped sludge and discharged effluent.

Initial Dilution

When a waste enters marine waters, either via discharge or dumping, it mixes with and entrains seawater; in addition, the wastestream begins to broaden and particles begin to disperse. As a result, the waste is diluted substantially, often by a factor of 5,000 or more. This initial *dilution* takes place within the first few hours after disposal and lasts until waste particles either cease moving vertically in the water column or reach the bottom (280,385).

Figure 11.—General Fate of Sewage Sludge Dumped in Marine Waters



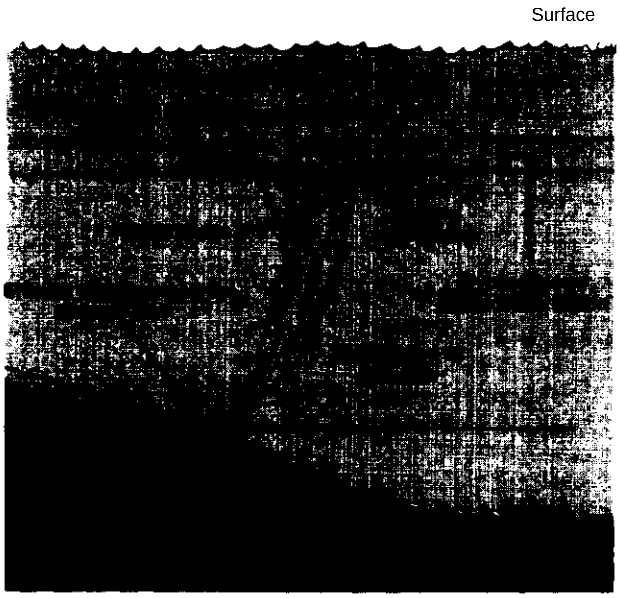
SOURCE" Off Ice of Technology Assessment, 1987; after U S Environmental Protection Agency, Intra-Agency Sludge Task Force, *Use and Disposal 01 Municipal Sludge*, EPA 625/10-84-003 (Washington, DC: September 1984)

Vertical movement of waste particles in the water column depends on the waste's bulk density[4] and the presence of pycnoclines (286). Waste particles that are more dense than the surrounding water will sink, while less dense particles will rise. This vertical movement continues until the waste particles reach a water layer or pycnocline of the same density, or the bottom. Particles that accumulate along pycnoclines eventually are transported by other processes or settle to the bottom.

[3]These biological transport processes are distinct from the biological processes of bioaccumulation and biomagnification discussed later,

[4]Bulk density is the weight of a waste per unit of volume

Figure 12.—General Fate of Effluent Discharged Into Marine Waters



SOURCE: Office of Technology Assessment, 1987; after US. Environmental Protection Agency, Office of Water Program Operations, *Report on the Implementation of Section 301(h)*, EPA 430/9-84-007 (Washington, DC: August 1984).

This description is simplistic because wastes usually are not homogeneous; instead, they usually are composed of a variety of particles with different densities and are not uniformly diluted (132,286). Lighter, floatable materials (e. g., plastics, oil, or grease) generally rise to the surface, while heavier materials remain at lower depths.

Physical Transport

Physical transport generally results in the dispersion of particles and pollutants away from the disposal site. Two major physical processes are largely responsible for dispersion: *currents* that move water or other matter from one place to another and *mixing* of waters with different characteristics.

There are two general categories of currents: permanent and transient (473). Permanent currents are found in coastal and open ocean waters (e. g., the strong Gulf Stream off the east coast and the weak California Current off the west coast). Portions of these currents (called eddy rings or jets) can meander from the main current and modify the net direction of waste material transport (120). The effects of long-term currents are particularly important when evaluating potential dumping sites.

Transient currents occur over smaller distances and time periods than permanent currents. They are found in all marine environments, including estuaries, and are caused by factors such as winds, tides, and waves. Their effect on the transport of waste material tends to be most important when wastes are discharged or dumped near shore. For example, currents close to shore and at or near the surface can move sediment such as dredged material along the shoreline (2 10,473).

Mixing occurs when two masses of water with different densities (e. g., two currents, or a current and a relatively stable water mass) intermingle along their common boundary (262). This is generally caused by random motion along density gradients, but it can be enhanced by wave action and tides (48). Its effects vary in different marine environments. For example, mixing of bottom and surface waters in the open ocean can take hundreds of years (48, 120). In estuaries and some coastal waters, mixing can occur immediately after disposal and increase dilution of the waste material.

Currents and mixing can transport and disperse wastes over hundreds of kilometers (120,286). The depth at which such transport occurs depends on the presence of pycnoclines, because particles tend to fall until (and if they reach a layer of water denser than the particles themselves. For example, particulate matter from dumping activities in the New York Bight generally descends to the depth of a seasonal pycnocline and then is transported laterally (426,709).

Biological Transport

Waste particles and pollutants can be extracted from the water column by plants and animals in various ways, including direct ingestion, passing through gills, or other mechanisms. Once extracted, the wastes can be transported from one location in the water column to another by several processes that are associated with individual organisms.

Migration by Organisms.—Many organisms move relatively long distances as part of their normal living pattern and, as a result, they can carry waste particles and pollutants to new locations.[5] The organisms can move either vertically (i. e., up and

[5] Pollutants can also be transported out of the water, for example when predatory birds consume contaminated marine organisms.

down in the water column) or horizontally (e. g., from coastal waters into estuaries). For example, some plankton move vertically in the water column on a daily basis and certain fish exhibit similar movements on a seasonal basis. Tuna and certain marine mammals are well-known for their lengthy horizontal migrations.

Many organisms must move from coastal or open ocean waters into estuarine waters to breed and/or to provide proper nursery habitat for their offspring. Some organisms such as salmon migrate from marine waters to rivers to breed; fish that undertake such migrations are known as anadromous fish. These migratory organisms can be exposed to a variety of pollutants while they migrate.

Movement of Eggs and Body Remains .—Many organisms lay eggs that are carried by currents to other areas or that move vertically depending on their relative buoyancy; for example, some eggs sink to deeper waters while others rise to the microlayer. In some cases, pollutants may have been incorporated into the eggs as they were formed, which occurs frequently in the surface microlayer. In addition, once an organism dies, its remains can be moved to new areas by similar means and these remains also can contain pollutants.

Excretion. —When a marine organism ingests waste materials, they often can eventually be excreted. Since many organisms move substantial distances in the course of their daily activities, excretion can occur in locations far from the point of ingestion. If excreted by organisms inhabiting the water column, excretory products often settle to the seafloor; if excreted by benthic organisms, the products generally remain on the seafloor.

Sediment Deposition

The processes discussed so far transport substances throughout the water column. Other processes, particularly sedimentation and flocculation, influence the manner in which particulate material and associated pollutants are deposited on the bottom. Two additional processes, resuspension and bioturbation, can counter this, but generally only to a small degree. The combined effects of these processes determine the overall rate of accumulation of particulate matter on the bottom.

Sedimentation is the settling of particulate matter through the water column and onto the bottom. The rate of sedimentation depends on particle size and density, water density, mixing, and flocculation, For example, larger particles tend to be heavier and they settle faster than smaller particles. The presence of pycnoclines can alter the rate of movement of particles; particles that reach a layer of similar water density generally cease moving and remain at the pycnocline, at least until some other transport processes move them elsewhere.

Flocculation refers to chemical reactions that result in the aggregation of small particles into larger particles, thus increasing particle size, density, and settling rate. Flocculation often occurs at the boundary of freshwater and saltwater, such as when freshwater effluent containing metals encounters more saline estuarine water.

The method of disposal and the concentration of solids in the waste also can affect both sedimentation and flocculation (385,596). For example, wastes dumped from a ship often have a higher concentration of particles (even after initial dilution) than do pipeline effluents and may exhibit higher rates of flocculation and sedimentation. In addition, the settling rate may be increased because dumped materials have a greater downward momentum.

In well-mixed waters that do not exhibit pycnoclines, particles can settle directly to the bottom. If physical transport processes are sufficiently strong to widely disperse the particles, however, the rate of particle accumulation on the bottom in a given area will be relatively low. In contrast, if wastes are disposed of in shallow or quiescent estuarine and coastal waters, or even in some deeper coastal waters at a high and continuous rate, sedimentation and flocculation can be significant and cause an accumulation of particulate material on the bottom. Such accumulations can alter the particle size or chemical composition of bottom sediments, which can in turn affect benthic organisms and the structure of benthic communities.

Even after it settles to the seafloor, particulate matter can be *resuspended* back into the water column. For example, bottom currents and storms are capable of stirring up sediments and moving settled particles back into the water (139,385). The physical characteristics of the particles influence resuspension; for example, silt and clay particles are more cohesive than sand particles and are less likely to be resuspended (596). Resuspension can also be caused by chemical and biological processes. For example, when bacteria in the sediments decompose particulate matter with a high organic content, some byproducts of decomposition can be released into the water column. In some cases, this can include pollutants such as metals, Predicting resuspension rates generally is difficult and site-specific (262).

In another biological process that affects sediment deposition, burrowing animals can move particles and associated pollutants toward or away from the boundary between the sediment and the water column, a process known as *bioturbation (385).* As a result, pollutants such as polycyclic aromatic hydrocarbons and polychlorinated biphenyls (PCBs) can either be brought into contact with the water column, where non-burrowing organisms can be exposed to them (295,385), or buried more deeply in the sediments.

POLLUTANTS AND THEIR RELATIONSHIP TO IMPACTS

The wastes and pollutants disposed of in marine waters can have varying impacts on marine environments and organisms. The relationship between different pollutants (i. e., oxygen-demanding substances, nutrients, suspended solids, pathogens, metals, and organic chemicals) and impacts can be complex, depending on what biological, chemical, and physical processes occur to catalyze the impacts.

Oxygen-Demanding Substances

Minimum levels of oxygen are critical for the maintenance of most forms of life. Oxygen levels in the water and sediments can decline, however, as a result of several common processes. First, microorganisms use oxygen to decompose or transform organic material, which is contained in most wastes, into compounds such as carbon dioxide, water, and nitrates. The amount of oxygen used during this process is termed the biochemical oxygen demand (BOD) (132,418). Second, waste material is also broken down by chemical processes (independent of organisms) that use oxygen; the total amount of oxygen that can be used in biological and chemical processes is termed chemical oxygen demand (498). Oxygen levels also can decline as a consequence of nutrient enrichment, which is discussed below.

When the amount of dissolved oxygen in water falls below a critical level, often around 2 parts per million, the water is said to be hypoxic, Water that is completely depleted of dissolved oxygen is called anoxic. Hypoxic and anoxic conditions can cause massive fish kills; if oxygen levels are reduced only slightly (but not enough for conditions to be considered hypoxic), organisms can still be stressed and chemical reactions in the water column can be modified. These problems are more common in estuaries and coastal waters than in the open ocean, where waters are generally more dispersed and mixed.

Nutrients

Nutrients are essential for the proper growth and reproduction of individual organisms and, consequently, for the general productivity of marine environments. *Eutrophication* refers to an increase in nutrient levels in a body of water. This can occur naturally (e. g., in the open ocean through the upwelling of nutrients from deep waters) or as a result of human activities (e. g., runoff from fertilized farmlands or discharges from sewage outfalls). In either case, the addition of nutrients such as nitrogen and phosphorus can lead to increases in the productivity of marine organisms, particularly some algae. Up to a certain limit, such increases in productivity can be beneficial, for example, by leading to corresponding increases in fish populations in areas where nutrients are relatively lacking. However, if nutrient levels are too high, several adverse impacts can occur:

- increased turbidity or cloudiness of the water, which can keep light from reaching submerged vegetation;
- changes in the distribution, abundance, and diversity of species (e. g., the replacement of typically abundant species with less common species);

- subsequent changes in food chain relationships (165); and
- depletion of oxygen levels when large numbers of algae die and are decomposed by microorganisms; oxygen depletion in turn can cause other changes including fish kills.

Increased nutrient levels are more common in estuaries and coastal waters than in the open ocean. Large quantities of nutrients enter estuaries and coastal waters from rivers, runoff, and disposal, as well as from coastal upwelling. In addition, processes that dilute and disperse nutrients are weaker in these waters.

Suspended Solids

Marine plants generally grow best in relatively clear water where sunlight, which is critical for photosynthesis, can penetrate to and be used by the plants. Since the introduction of suspended solids into shallow waters can increase turbidity and block out sunlight, it can reduce the rate of photosynthesis significantly and harm submerged vegetation. In addition, solid particles can settle out of the water column and accumulate on the bottom, sometimes changing the nature of the sediments and associated benthic community. In addition to solids suspended in the water column, the solid material in a waste can bury and kill benthic organisms (e. g., if large amounts of dredged material are disposed of in a small area).

Pathogens

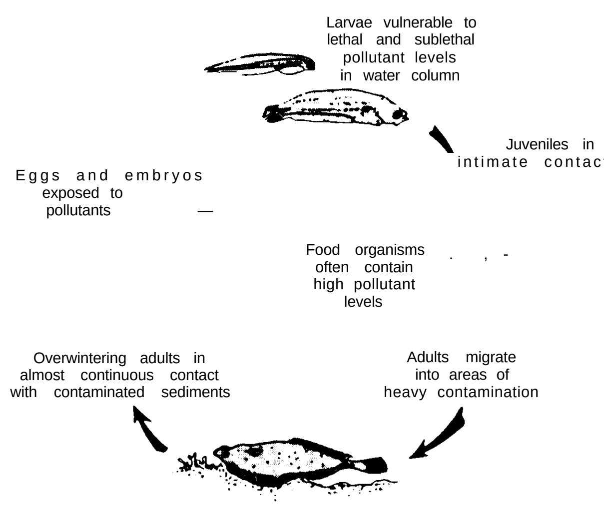
Many pathogens—including viruses, bacteria, fungi, and parasites—that can cause human disease are found in marine environments. The viability of pathogens depends primarily on their survival after they enter a particular marine environment. While many pathogens die quickly after exposure to various environmental factors (e. g., light), some can persist, especially if adsorbed onto particulate matter that provides protection from the surrounding environment (183,205). In addition, some pathogens can be ingested by and survive in marine organisms without harming the organisms, but they can cause serious human health effects if a person consumes an organism that has ingested but not yet excreted the pathogens. For example, shellfish "filter" water to obtain food and, in the process, can ingest pathogens; the concentration of pathogens in the gut of a shellfish can be quite high. Detecting pathogens that survive in marine waters is often difficult, as is predicting the impacts they can cause.

Organic Chemicals and Metals

Whether toxic pollutants such as metals and organic chemicals cause adverse effects depends on the interaction of many chemical and biological factors. Only some toxic pollutants are *bioavailable* to organisms, that is, present in a form to which organisms can actually be exposed. Many metals, for example, are attached to particulate material and buried deep in sediments where they are exposed to few organisms. If a pollutant is bioavailable, the effects of exposure will vary depending on its concentration and the length of exposure (270), as well as the stage in the organism's life cycle (figure 13).

Not all metals and organic chemicals cause adverse effects, even if an organism is exposed to and takes up a pollutant. In fact, organisms require small amounts of some metals that occur naturally in marine waters for important physiological functions. Other pollutants may be present in forms that

Figure 13.—Life Cycle of the Winter Flounder and Potential Contact With Chemical Pollutants



NOTE: An individual flounder could come into contact with pollutants at one or more stages of its life cycle.

SOURCE: C.J. Sindermann, "Fish and Environmental Impacts," *Archiv für Fischereiwissenschaft, 35125-160,* 1984.

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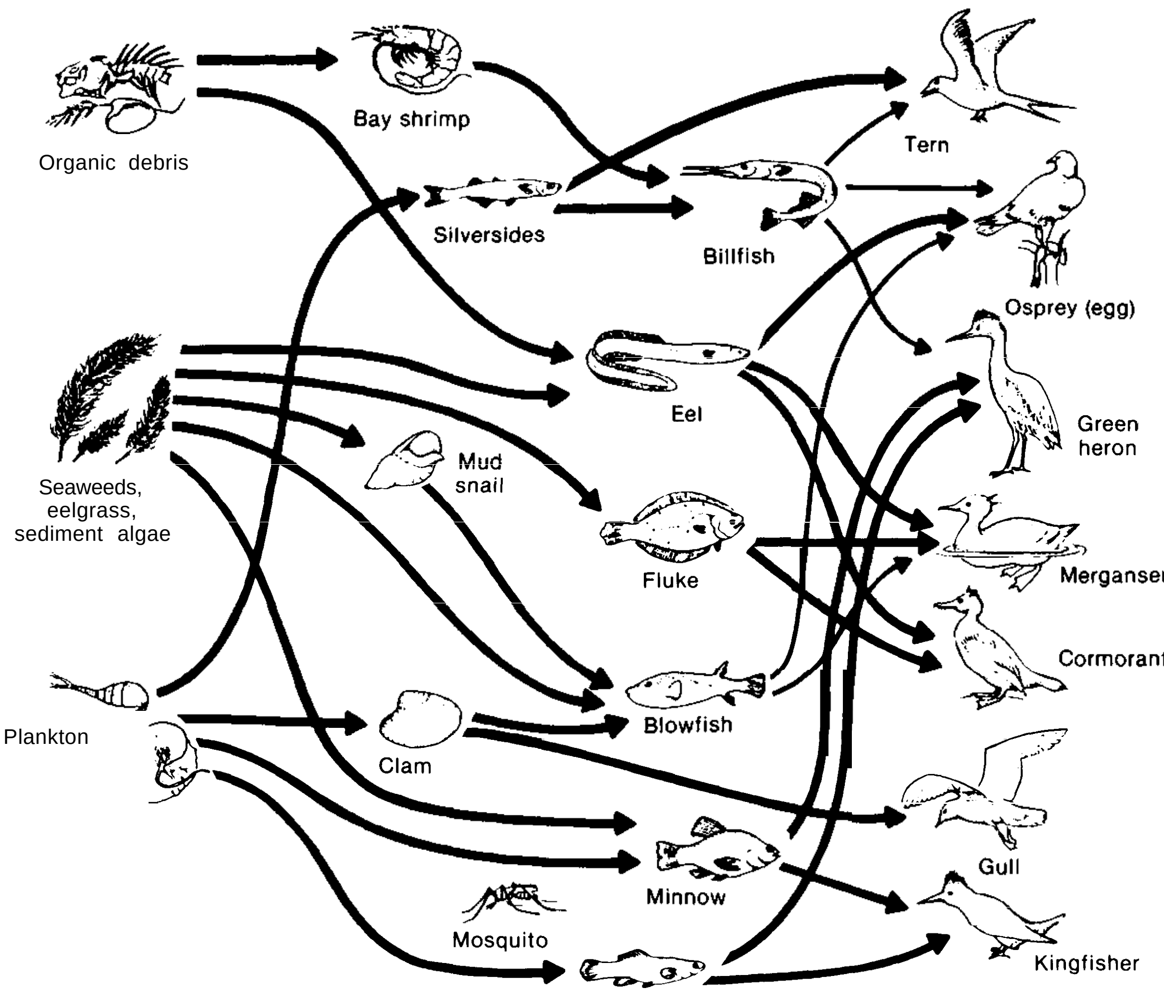
Figure 14.—The Transfer of DDT Through a Portion of a Food Web in the Long Island Estuary



Persistent, lipid-soluble pollutants such as DDT can be taken up from the water column or sediments by many organisms. This diagram depicts the many pathways by which a pollutant such as DDT can be transferred up the food chain and eventually accumulate in high concentrations in the tissues of fish-eating vertebrates.

SOURCE Office of Technology Assessment, 1987; after B W Pipkin, et al, *Laboratory Exercises in Oceanography* (San Francisco, CA W.H Freeman & Co , 1977)

are not toxic to organisms; they may stay in the gut for varying periods and then be excreted without causing harm (262,385).

Two important processes determine the ability of many metals and organic chemicals to cause adverse impacts on marine organisms or humans: bioaccumulation and biomagnification. *Bioaccumulation* is the process whereby a substance enters an aquatic organism, either from the water or from consumed food, and is stored within the organism's tissues. *Biomagnification* refers to increases in the concentrations of bioaccumulated substances in the tissues of consumers and predators occupying successive levels of a food chain (58,260). The likelihood of adverse impacts on organisms such as invertebrates, fish, or humans is increased if toxic pollutants biomagnify in a food chain (figure 14). The effects might show immediately after exposure or take long periods to appear, and correlating them with degree and duration of exposure is difficult.

Bioaccumulation can occur at any level of the food chain. For example, phytoplankton can be contaminated by pollutants present in the water column, while benthic zooplankton and shellfish

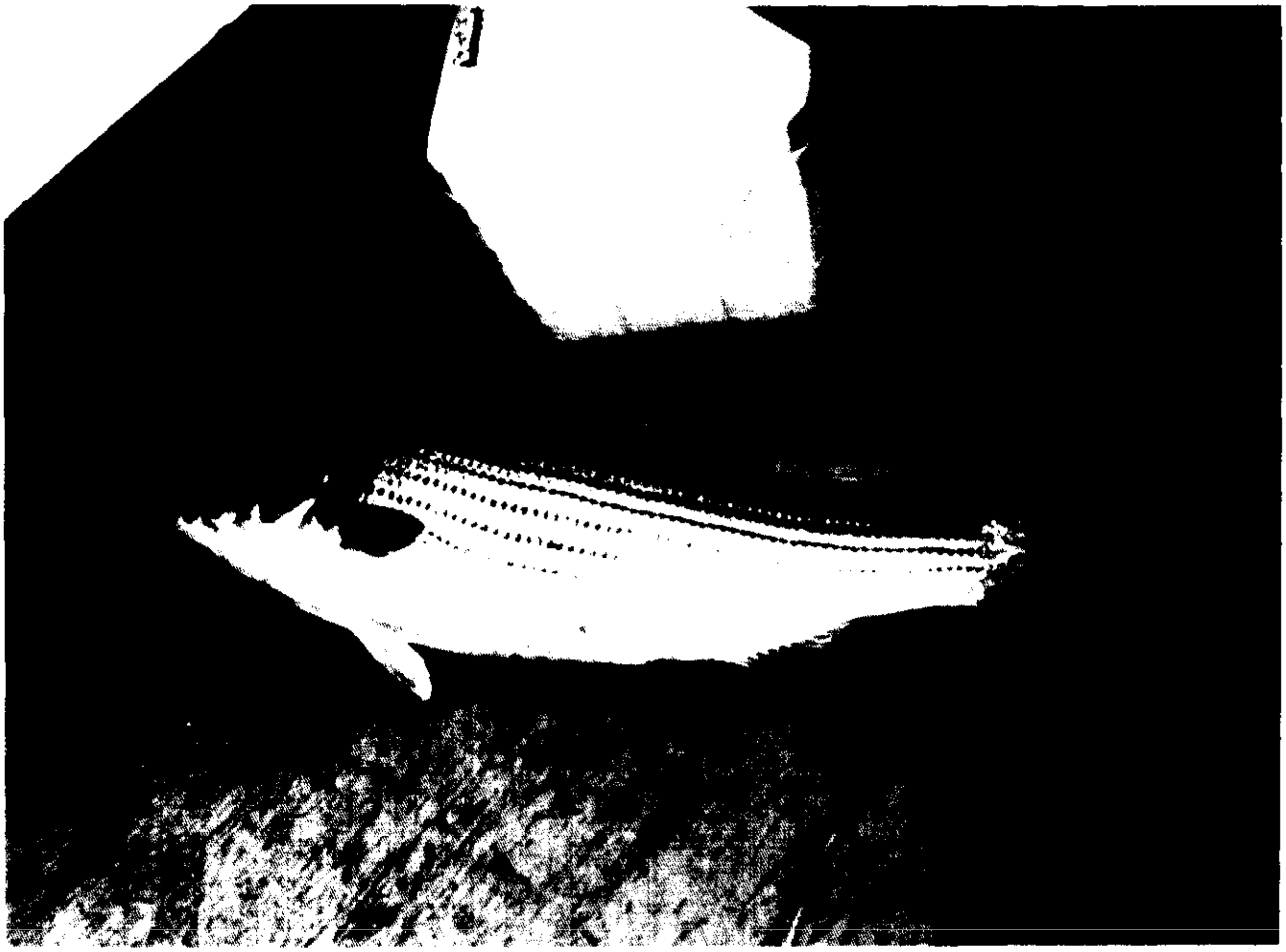


Photo credit: US. Fish and Wildlife Service

Healthy striped bass have long supported a valuable commercial and recreational fishery along the Atlantic Coast. The fishery has declined significantly during the last 15 years, and many individual fish are severely contaminated with PCBs.

that filter bottom sediments in search of food can ingest pollutants that are adsorbed onto sediment particles. These organisms can then contaminate organisms in higher trophic levels that ingest them as food (41 O). However, bioaccumulation does not always cause adverse impacts. Some organisms can internally degrade or regulate the levels of certain toxic pollutants in their systems.

It is also possible for some toxic pollutants to cause problems even if they do not bioaccumulate. For example, some pollutants can be concentrated in the gut of an organism (but never bioaccumulate in the organism's tissues); these pollutants, however, can often cause adverse effects on predatory organisms higher in the food chain. In addition, some behavioral effects can occur even if a pollutant is not ingested. For example, herring have avoided waters they typically use for spawning because of pulp mill effluents discharged into a river (398).

Organic Chemicals

Organic chemicals, whether dissolved in the water column or adsorbed onto sediment particles, can be taken up by an organism in several ways, such as through filtering water or sediment or ingesting other organisms. Whether bioaccumulation occurs depends primarily on a chemical's ratio of lipid volubility to water volubility (165,195,262, 385). Some organic chemicals are more soluble in water and can pass through an organism (or be metabolized by the organism), while others are more soluble in lipids and will bioaccumulate in fatty tissues. For example, PCBs are soluble in lipids and are only slowly metabolized by marine animals, so they tend to bioaccumulate in an animal's fatty tissues (139). Birds (such as bald eagles and pelicans) and mammals (such as seals and sea lions) that occupy higher levels of marine food chains usually have large amounts of fatty tissues and are particularly likely to bioaccumulate organic chemicals.

Bioaccumulated organic chemicals can affect organisms at all levels of food chains. Halogenated organic chemicals (including pesticides such as DDT) are the most likely organic chemicals to be biomagnified because they are persistent and highly soluble in fatty tissues.[6] PCBs cause decreases in plantlife and changes in community structure, and they have been implicated in fish mortality and physiological abnormalities (132,133,139).

Some organisms have the ability to degrade some organic chemicals into other forms. For example, microorganisms can degrade some highly persistent and toxic chlorinated compounds under certain conditions (40,41 ,540). Some invertebrates, fishes, and mammals can partially degrade polycyclic aromatic hydrocarbons and PCB, but the byproducts can sometimes be more toxic than the parent compound. The bioavailability and toxicity of organic chemicals can also be modified prior to ingestion by processes such as bioturbation or degradation by light (385,710).

Metals

The ability of a metal to affect marine organisms depends primarily on its *form (e. g.,* dissolved or particulate, bound to another substance or free), and this is greatly affected by site-specific conditions. In their *particulate* form, most metals tend to adsorb onto other particles that eventually settle from the water column and are deposited as sediment (139, 165). Once deposited in typical oxygen-poor sediments, the chemical form of these metals is generally stable.[7]

[6] The term halogenated refers to compounds that include certain elements such as fluorine, chloride, and bromine.

[7] Microorganisms in sediments, however, can modify the form of some metals; for example, bacteria can convert slightly toxic inorganic mercury to highly toxic and volatile methyl mercury (26).

If the sediments are subsequently oxygenated, however, some metals (such as cadmium, copper, nickel, and zinc) may dissolve and be slowly released back into the water column, where they may be taken up by non-benthic organisms (124). For example, zinc is very insoluble when combined with sulfide in oxygen-poor environments but is soluble in oxygen-rich environments (385). Sediments can be oxygenated (and also resuspended) by bioturbation, storms, and other disturbances (139). Metals also can be released as a result of other changes such as salinity fluctuations in estuaries.

Metals present in the water column as dissolved ions often bind with other molecules to form soluble complexes that can affect bioavailability and toxicity to organisms (385). For example, the toxicities of lead and zinc are reduced when they are in complexes, while the bioavailability and toxicity of methyl mercury is greatly enhanced (75,247).

Marine organisms can ingest metals that are dissolved in the water or they can ingest particulate matter onto which metals are adsorbed (46,232, 260). Once ingested, some metals can pass through the gut and be excreted, while others cross the gut membrane and bioaccumulate in organismal tissue (410). Of the four metals of primary concern to humans (ch. 6), cadmium and mercury tend to bioaccumulate in marine organisms, while neither arsenic nor lead have been shown to bioaccumulate significantly in seafood (lead, however, can be present in high concentrations in the guts of some shellfish). Mercury in its methylated form, however, is the only metal known to biomagnify in successive levels of aquatic food chains.

Some organisms can regulate the internal availability or level of certain metals (133, 139). In some fish, for example, metals that are toxic as free-floating ions (e. g., cadmium, copper, mercury, and zinc) can be bound to the protein metallothionein and the bound metals are generally not toxic (250, 410), Proteins with similar capabilities occur in crustaceans and mollusks (74). Arsenic is largely converted to nontoxic forms by marine organisms. Some metals also may be deposited in skeletal material and intracellular spaces, or removed from an organism via excretion, diffusion, molting, or egg production.

CAN MARINE ENVIRONMENTS ASSIMILATE WASTES OR RECOVER FROM IMPACTS?

Two concepts are often used in discussions about the role of marine environments in waste disposal: assimilative capacity and recovery. *Assimilative capacity* has been defined as the amount of material that could be contained within a body of water without producing an unacceptable biological effect (188). Recovery refers to the degree to which a condition that existed prior to an impact is restored. In essence, the assimilative capacity concept asks how much waste can be added to a marine environment before an impact occurs, while the recovery concept asks what happens after inputs of wastes and pollutants cease.

Both concepts have an intuitive appeal, and even some utility as concepts that can illuminate general discussions, but applying them in actual practice is difficult. This difficulty stems primarily from the inability to develop quantitative criteria for assessing questions such as:

- What is an impact and what is an unacceptable level of such an impact?
- At what ecological level should impacts be measured (e. g., on cellular systems, organisms, populations, general habitat qualities)?
- How many impacts must be reversed (and to what degree) before an area is considered to have recovered?
- Over what time scales and sizes of areas should assimilative capacity or recovery be measured (20, 165, 188)?

Both assimilative capacity and recovery depend on many site-specific factors including: the physical and chemical characteristics of the receiving waters (e. g., strength of currents and mixing, sedimentation, adsorption of pollutants); the resiliency of organisms that inhabit the area (e. g., their ability to survive, grow, and reproduce); and the ability of other organisms to migrate into the area. These questions might be answered at a specific site *if acceptable quantitative criteria could be developed,* but both assimilative capacity and recovery would still vary from site to site and would have to be determined on a case-by-case basis.[8]

Clearly, some wastes can be disposed of under certain conditions without causing severe adverse impacts. Furthermore, some marine environments are not as likely as others to suffer certain impacts and therefore could be considered to have a greater assimilative capacity with respect to those impacts. For example, the open ocean is less likely to exhibit hypoxia and eutrophication and therefore might be able to assimilate oxygen-demanding substances and nutrients to a greater extent than can estuaries and coastal waters.

Marine environments also can recover from some impacts, particularly when inputs of oxygen-demanding substances, suspended solids, and nutrients are reduced. For example, dissolved oxygen levels have increased markedly and anoxic conditions have declined following improvements in municipal sewage treatment plants in the upper Delaware Bay estuary and in Newark Bay (346, 683). In addition, some estuaries and coastal waters are subject to large natural fluctuations in physical conditions (e. g., tides, waves, storms). Organisms in these environments show large natural population fluctuations, as well as rapid growth and migration rates. These organisms may be able to survive catastrophic events or repopulate an area quickly, often in as little as one year (165).

In contrast, marine waters cannot readily assimilate many organic chemicals or recover from their impacts, primarily because of the persistence of many of these pollutants. For example, ‘ ‘hot spots’ ‘ of DDT still exist in some coastal sediments and some fish species contaminated with DDT are still being caught (e. g., the white croaker off the southern California coast), even though most uses of DDT were prohibited in the United States in 1972. For these persistent organic chemicals, the length of time under consideration greatly influences any assessment of assimilative capacity and recovery potential, and in some cases, even if all pollutant inputs were halted, the environment still

[8]Another concept, *accommodative capacity*, has been proposed as a replacement for assimilative capacity (284). Accommodative capacity has a slightly different focus in that it emphasizes how an environment ''adjusts to overall inputs of pollutants. However, it suffers from similar shortcomings, for example, its dependence on defining the term ‘ ‘adjustment,

may not ever return to its unpolluted state. As an illustration, consider the sediments in portions of Buzzards Bay, Massachusetts, which are contaminated with highly persistent PCBs. As the contaminated sediments are covered (naturally or artificially) with cleaner sediment, the potential for organisms to be exposed to the PCBs could decrease, and this could be considered a reversal of contamination. However, subsequent dredging of the harbor or the effects of severe storms could resuspend the sediment and PCBs and re-expose organisms to these pollutants.[9]

Moreover, most situations are complicated because multiple impacts and pollutants are typically involved. Assimilative capacity or recovery potential might be assessed for one impact, but they are much more difficult to determine for interrelated impacts. For example, it may be possible to determine how much waste can be disposed of before oxygen is depleted (i. e., assimilative capacity) or how quickly adequate oxygen levels will return following disposal (i.e., recovery rate). However, oxygen declines can cause other impacts such as fish kills and it can be difficult to ascertain when populations would recover to ''acceptable' levels. When multiple pollutants are involved it can be difficult to determine the effect of removing or reducing one pollutant from the total waste stream.[10]

[9]In some situations, however, impacts from organic chemicals clearly have lessened over time. For example, the population of brown pelicans in southern California, which declined because DDT caused eggshell thinning and subsequent reproductive failure, has steadily increased since the discharge of DDT was sharply curtailed (54).

[10]Tests to assess the toxicity of "whole' effluents (i. e., the cumulative toxicity of all pollutants in an effluent) are being developed by EPA.