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Water quality investigations and living resource assessments have demonstrated that parts of the Long Island Sound ecosystem are threatened, and that the most critical problem is hypoxia.

Hypoxia in Long Island Sound

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WHAT IS HYPOXIA?

Hypoxia, as used by aquatic scientists, is the technical term for low dissolved oxygen concentration in water. Because marine organisms need oxygen to respire just as we do, the amount of dissolved oxygen in the water is critical to the health of marine life. Low oxygen concentrations, depending on their duration and the size of the area affected, can have serious consequences for a marine ecosystem. Besides depriving organisms of oxygen, low dissolved oxygen can lead to the production of hydrogen sulfide, a toxic gas.

The amount of oxygen that water can hold, called saturation, varies with temperature, salinity, and pressure. When the water temperature at salinities and depths typical of Long Island Sound rises to a typical summer 22°C (or 72°F), saturation is about 7.5 milligrams per liter (234 micromoles per liter). An area becomes hypoxic when oxygen levels fall below a certain level. For Long Island Sound, that level is considered to be 3 milligrams per liter (Table 1). Hypoxia is known to occur during summer months in segments of estuaries such as Long Island Sound; Chesapeake Bay; Narragansett Bay (Rhode Island); Massachusetts Bay and Buzzards Bay (Massachusetts); and in a few open coastal areas such as the New York Bight.

To understand how water is sampled to test for dissolved oxygen concentrations, one can picture the water as a column extending from the surface down to the bottom sediments. When scientists want to measure hypoxia, they must sample throughout the water column, from the water's surface all the way to the bottom sediments.

The most variation in dissolved oxygen levels occurs close to the bottom. Since regular sampling of dissolved oxygen in the Sound began in 1986, research has shown that every summer the bottom waters of the western Sound become hypoxic. The duration and affected area of these events have varied from year to year (Figure 1,Table 2), but hypoxia generally occurs between July and September. During the winter, on the other hand, the entire Sound is generally well oxygenated.

Table 1

Dissolved Oxygen Concentration	Effect
0 - 0.5 milligrams per Liter	Inhospitable to living organisms other than bacteria that metabolize sulfur.
0.5 - 1 milligrams per Liter	Some benthic organisms can tolerate for a few days.
0 - 2 milligrams per Liter	More than 90% of benthic fishes and lobsters absent.
1.5 - 3.0 milligrams per Liter	Many pelagic, early life stages die within exposure duration of 1 to 4 days.
3 - 4.3 milligrams per Liter	25 to 50% mortality in some organisms in 96 hour laboratory exposures. Lobster and fish catches reduced in trawl samples compared to well-oxygenated waters.
5.0 milligrams per Liter	Believed to be protective of most Long Island Sound marine life.

Figure 1 Worst Hypoxic Conditions Recorded During Summer Months

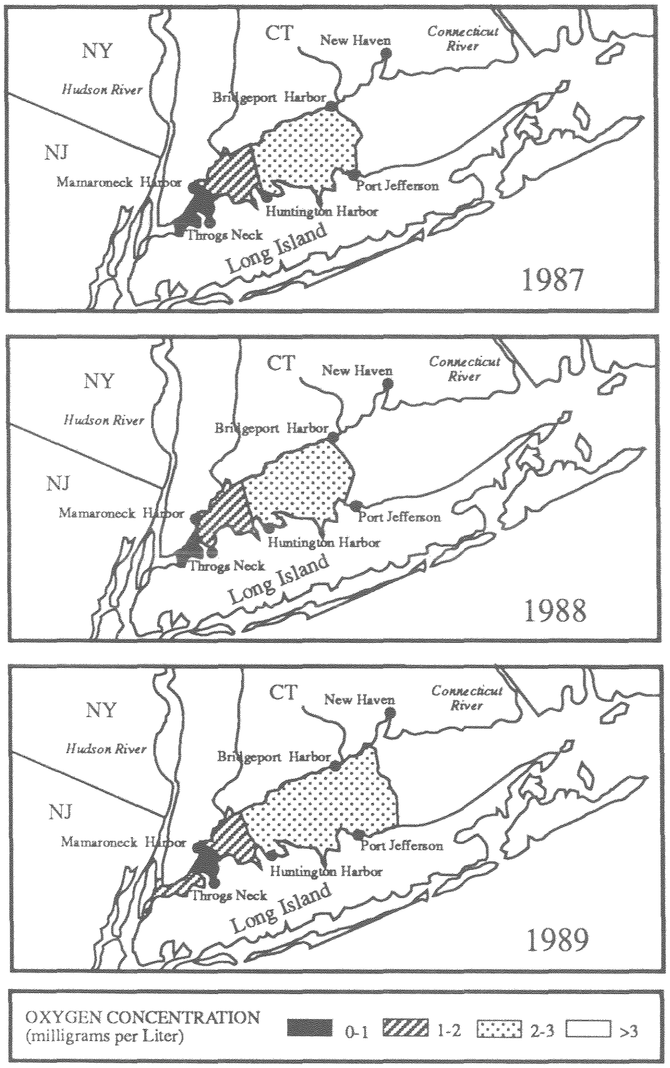

Table 2 Recorded dissolved oxygen levels and area affected during summer months.

DO Range (milligrams per Liter)	Area (square miles)		
	1987	1988	1989
<1	50	32	51
1-2	66	83	89
2-3	234	230	377
3-5	337	401	315
0-3	350	345	517

In 1987 when the most severe conditions were recorded, hypoxia in near-bottom waters extended from the Throgs Neck Bridge area in the westernmost part of Long Island Sound, eastward to the Bridgeport-Port Jefferson line (Figure 1). That year, dissolved oxygen concentrations in deeper waters in the westernmost sections dropped to nearly zero, a condition known as anoxia (the absence of oxygen). In 1989, oxygen levels did not drop quite as low, but the hypoxia event lasted longer and the total area affected was larger, extending approximately to the New Haven-Shoreham line. In 1990 hypoxia in the Sound was more limited in duration and extent, and 1991 data show conditions similiar to 1989.

WHY DOES HYPOXIA OCCUR?

Hypoxia occurs naturally in the summer in segments of deeper areas of estuaries such as Long Island Sound. Several characteristics of estuaries contribute to this phenomenon.

Salinity and Density Differences

Estuaries are bodies of water with a large freshwater input, mainly from rivers, and an opening to the sea. Long Island Sound has several major Connecticut tributaries (Connecticut, Thames, and Housatonic Rivers), which empty freshwater into it, lowering the salinity. Since freshwater is less dense (lighter) than saltwater, a lighter, less saline surface layer generally forms in estuaries.

Water from the East River, which borders the eastern shoreline of Manhattan, is carried into the sound with the tidal cycle. This river serves as a conduit into the Sound during incoming tides for sea water diluted by Hudson River water, together with outflow from sewage treatment plants in the area.

Temperature Differences

During the warm summer months, surface waters heat up, compared to deeper water. The warming surface water, already lighter than saltier water, becomes even less dense as water expands upon warming. The warmed, less saline surface water thus forms a distinct lighter layer over the saltier, colder bottom waters. This stratification--a rapid change in density with depth, called a pycnocline--restricts mixing and vertical movement of water.

Restricted vertical mixing in estuaries such as Long Island Sound make them particularly vulnerable to hypoxia. Water is saturated with oxygen at the surface where it interacts with the atmosphere. It is also well oxygenated throughout the sunlit surface layer where phytosynthesis by phytoplankton occurs. Movement of ocean water into the estuary in the lower layers also recharges it with dissolved oxygen, but only very slowly. Thus, the water at depths below light penetration and organisms in the bottom sediments depend mainly upon oxygen supplied from the upper layers of water via vertical mixing. But the pycnocline acts as a physical barrier, preventing oxygenated surface waters from mixing into deeper waters (Figure 2).

The pycnocline, however, does not prevent decaying organic material, such as dying or dead marine plants and plankton, from gradually sinking to the bottom. If the pycnocline prevents mixing between the surface layer and the rest of the water column, oxygen that is used up below the pycnocline (by marine life, including the bacteria that decompose the decaying organic material) will not be replaced. If the water remains stratified for an extended period, and the amount of organic material below the pycnocline is large enough, hypoxia or anoxia can result. Thus, long, hot summers with little storm acitvity to help mix the waters and bring oxygen to depths are periods when hypoxia is likely to occur.

In the autumn, cooling surface water temperatures and storm wind-driven waves combine to break down the pycnocline and reestablish the transport of oxygen throughout the water column. Water circulation (speed and volume of flow); stratification; weather patterns; and the severity of phytoplankton blooms are all important factors influencing the onset, duration, magnitude, and extent of hypoxia.

Even with greater vertical mixing, hypoxia can occur in cases when phytoplankton blooms are very dense and respiration by bacteria that consume the decaying cells, is very high. Although natural conditions in productive estuarine systems may lead to extended periods of stratification, and consequently hypoxia, the greatly increased human population bordering the Sound has increased the input of sewage-derived nutrients and organic matter, particularly organic carbon into the waters of Long Island Sound (see MSRC Bulletin, "Population Growth and the Coastal Ocean," Vol. 1, No. 3). This has served to extend the area in which hypoxia occurs, its frequency of occurrence, its intensity, and its duration beyond what had occurred naturally.

Increased Primary Productivity

Although estuaries make up less than one percent of the volume of the world oceans, they are the most biologically productive parts. Many plants and animals spend critical parts of their life cycles in estuaries. Part of the biological productivity of estuaries is related to nutrient cycling, which supports the base of the food web--the microscopic plants, called phytoplankton. Nutrients, especially nitrogen and phosphorus, are essential elements for the healthy growth of aquatic plants. However, researchers working in Long Island Sound have identified an excess of nutrients--nutrient pollution--as the cause of increased hypoxia in the Sound and they have identified nitrogen as the "limiting nutrient."

THE DYNAMICS OF HYPOXIA IN LONG ISLAND SOUND

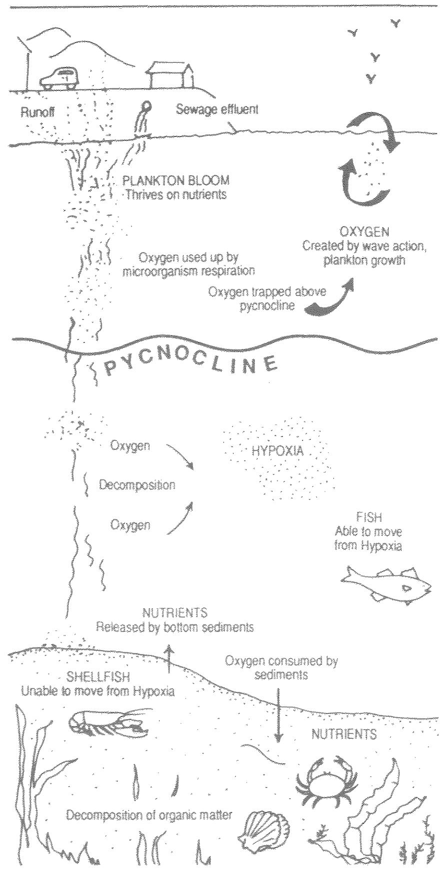

Figure 2

If a key nutrient (nitrogen in this example) is "limiting," increasing its abundance promotes further growth of the algae in the system. When excess concentrations are available, algal growth can continue uninhibited. In the Sound, the large levels of nitrogen are depleted during summer phytoplankton blooms, restricting or inhibiting further algal growth.

Excess nutrient discharges, especially nitrogen, can stimulate and prolong massive algal blooms. While there are a number of natural sources of nutrients to the Sound, such as rainwater runoff carrying wildlife excrement and decaying plant material, the amounts associated with human populations exceed all other sources: human waste from sewage treatment plants and septic systems, runoff carrying lawn fertilizers and pet excrement, and runoff from livestock farms and fertilized agricultural fields.

During phytoplankton blooms, which occur in the Sound from late winter through the summer and into autumn, billions of microscopic plants die each day and sink into the bottom waters where they are decomposed by bacteria and other microorganisms. During this decomposition process under certain conditions, microorganisms can deplete near-bottom waters of dissolved oxygen. In the hot summer months, when a strong pycnocline has formed and wind conditions are usually so mild as to be unable to break down the pycnocline, vertical mixing of the water column is obstructed. Relatively little mixing occurs between the oxygenated surface waters and the deeper parts of the water column. Oxygen depletion is further exacerbated by lower oxygen saturation levels at higher summer temperatures. Decomposition of such large amounts of dying phytoplankton uses up existing supplies of oxygen below the pycnocline and the result is hypoxia (Figure 2).

EFFECTS OF HYPOXIA

Scientists are still accumulating evidence on the magnitude of the threat to marine life posed by hypoxia, but within the past three years of intensive research, they have documented serious effects. Fisheries biologists who collect fish samples during hypoxic events have found that fish and other mobile marine life move away from low oxygen areas, while less mobile bottom dwellers (snails, shellfish) are stressed or suffocated (Figure 2). Data from trawling the entire Sound from 1986-1989 document that, compared to the less severely impacted mid-Sound area, the western Sound, on average, has fewer fish (Figure 3) and wider

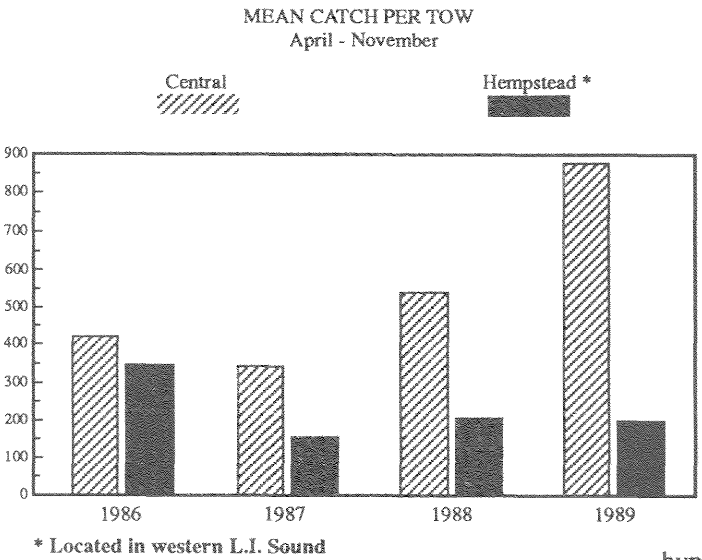

Figure 3

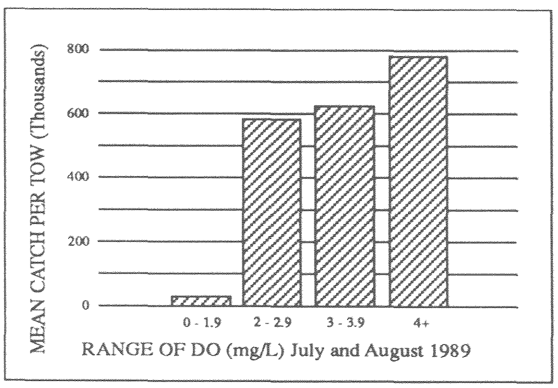

Figure 4

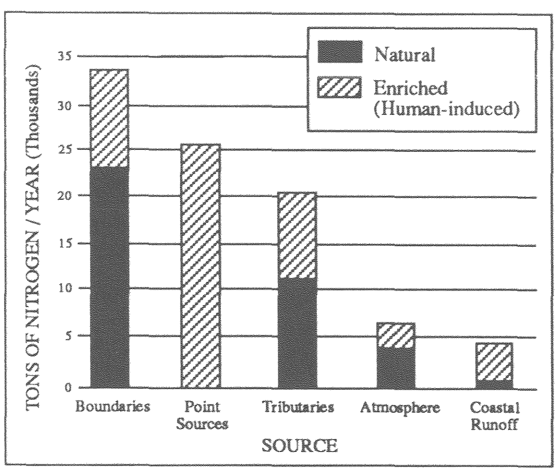

Figure 5

fluctuations in total numbers of fish, as well as fewer fish species. Although it cannot be concluded that hypoxia is the cause of these findings, laboratory studies of eggs and larvae of fish and lobster indicate that they can die when exposed to hypoxic waters. Mortality from hypoxia or migration from hypoxic areas can impact the food chain and at least the near-future productivity of the fishery (Figure 4).

UNDERSTANDING HYPOXIA

A great deal of research on hypoxia has been conducted as part of the U.S. Environmental Protection Agency (EPA) sponsored Long Island Sound Study. The study involved collecting and examining large numbers of samples of both water and sediments throughout the Sound. One group of researchers determined that due to the build-up of organic matter on the bottom, sediments account for a large portion of the oxygen demand in near-bottom waters. Another group of researchers focused on determining the magnitude of oxygen uptake in the water column. Their findings show that both the water column and the sediments are major sites of oxygen uptake when the water column is stratified and that bacteria and protozoa consume the majority of the oxygen, both in the water column and in the sediments.

In the water column, these organisms use a large amount of oxygen while consuming carbon from decomposing organic material. This organic material is supplied both from the nutrient-laden water (organic matter from sewage treatment) and from the dying phytoplankton. In and near the sediments, where hypoxia and anoxia occur, the organisms use up oxygen while consuming the sinking organic matter from the decaying phytoplankton cells.

MANAGING HYPOXIA

In studies such as the Long Island Sound Study with large amounts of physical, biological, and chemical sampling data, information gleaned from collecting and investigating the samples is often used to create a "model" of what happens when some aspect of the ecosystem is changed, for example, when nutrients are reduced. When data from monitoring water quality in Long Island Sound revealed the magnitude of the hypoxia problem, state and federal governments supported a computer modeling effort to better understand its causes, to simulate the extent of present and future hypoxic conditions, and to determine what could be done about it. The model, which describes chemical and biological interactions and water circulation patterns in the Sound, will be used as a management tool for analyzing the system, predicting its responses to human activities, and prescribing management actions to reduce nutrient input and increase dissolved oxygen.

The model differentiates between "natural" (background) versus human-induced contributions from each nutrient source (Figure 5). Sources are categorized as point or nonpoint pollution. Point sources originate at a specific point or place, such as a sewage treatment plant discharge pipe, while the origins of nonpoint pollution are diffuse--from throughout the watershed[1]. Major natural sources which account for about 44% of the total nitrogen entering the Sound are

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[1]The subject of point and nonpoint sources of pollution will be discussed in a future Bulletin.

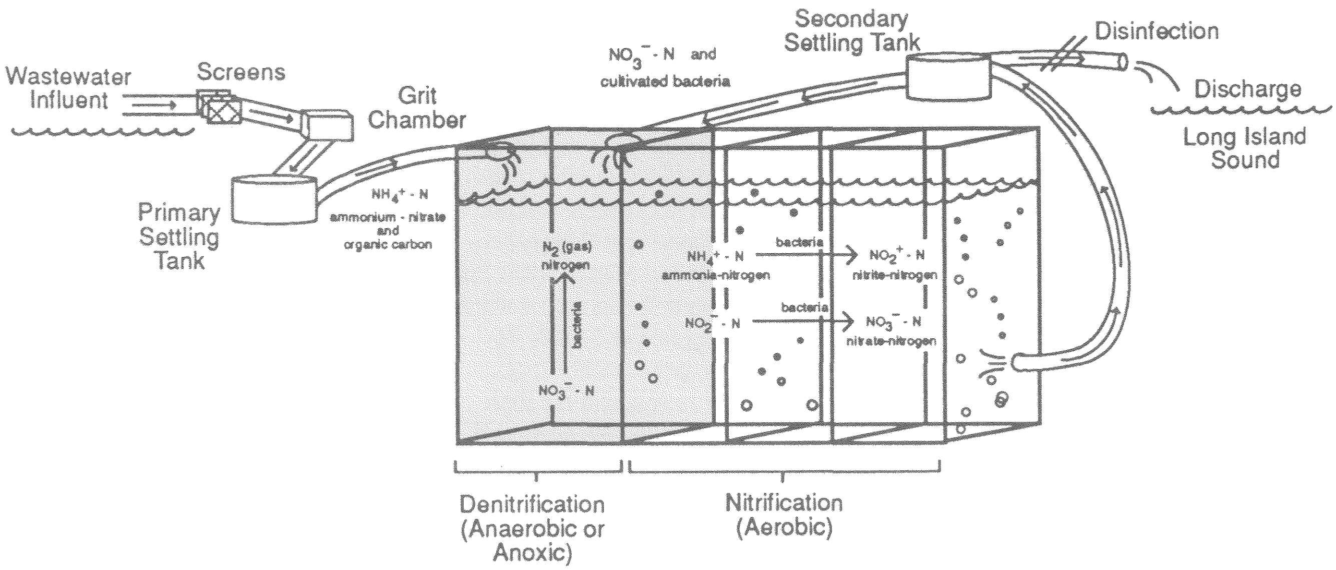

Figure 6 Example of biological nutrient removal process in an altered aeration tank.

nonpoint sources: rivers (tributary), the atmosphere (through rainfall) and the large quantity of Atlantic ocean water entering the Sound through its eastern "boundary" at the Race. The remainder is generated by human activity. Well over half of this portion comes from point sources, predominantly sewage treatment plants directly bordering Long Island Sound and along the East River.

POINT SOURCES OF NITROGEN

Since point sources are technologically easier to control than non-point sources, they are the major target of regulatory and management efforts. One management option to alleviate hypoxia is to reduce nitrogen inputs from the 44 sewage treatment plants that discharge over 1 billion gallons of partially treated sewage into Long Island Sound each day. Currently, wastewater is treated by two processes, called primary and secondary treatment, before being discharged into the Sound. Through settling, primary treatment removes solids and some organic matter, while secondary treatment uses biological processes (decomposition by bacteria and other microbes) to treat wastewater to further reduce organic wastes in the effluent.

Conventional primary and secondary wastewater treatment plants remove only small amounts of nitrogen and phosphorus. Typically, a primary treatment plant can remove 5 -15% of the total nitrogen and phosphorus from the waste stream. A secondary treatment plant will remove an additional 10-20% of these nutrients. Of the 44 sewage treatment plants surrounding Long Island Sound, only one (Mamaroneck Harbor facility) has not yet been converted to secondary. However, periodically, large amounts of untreated sewage flow directly into the western Sound. During and immediately following rainfall, because many of the New York City septic and storm sewers were combined when built over 100 years ago, large volumes of water reach treatment plants all at once. The plants overflow, spilling untreated sewage through combined sewer overflow (CSO) drains directly into the receiving waters (see Bulletin, "Floatable Wastes in New York Coastal Waters," Vol.1, No. 2).

Another form of sewage treatment is called tertiary. One type of tertiary treatment, biological nutrient removal (BNR), shown in Figure 6, transforms nitrogen, which enters the plant as ammonia (NH_4^+) into harmless nitrogen gas (N_2) that is released into the atmosphere. BNR is a two-step process utilizing the natural reactions of nitrification and denitrification. Figure 7 illustrates the nitrogen cycle in nature.

To set up BNR for wastewater treatment, the aeration tank is altered so that an anaerobic (when organisms use up oxygen during respiration),

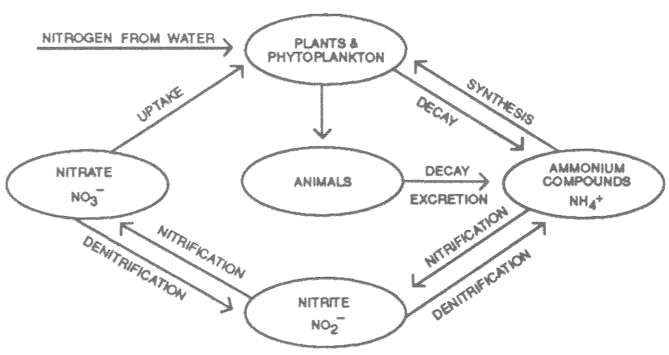

Figure 7 Example of nitrogen cycle in nature. Adapted from Garrels, Mackenzie and Hunt, 1975.

anoxic zone is created at one end of the tank, and the other sections remain aerated and aerobic (Figure 6). Sewage and bacteria from secondary settling tanks are mixed into the low oxygen zone. In the aerated sections, ammonia is converted to nitrate (NO_3^-) in a two stage reaction called nitrification. The next step is denitrification. This reaction, which requires low oxygen conditions, is achieved by extraction of oxygen from nitrate by bacteria. The end product is harmless nitrogen gas, which is released into the atmosphere. Consequently, total nitrogen concentrations in the wastewater effluent (discharge water) are reduced.

Several BNR techniques are currently being evaluated at three Long Island Sound sewage treatment plants: Norwalk Harbor and Stamford facilities in Connecticut, and Tallman Island in New York City. The goal of these experiments is to achieve 80% nitrogen removal from the effluent and to document operational limits associated with the process, such as how effective these techniques are in colder temperatures when bacteria are less active.

NONPOINT SOURCES OF NITROGEN

The remaining fraction of human-generated nitrogen input to the Sound--the part not accounted for by point sources--comes from nonpoint sources, including stormwater runoff, combined sewer overflow and direct runoff from fertilized land. The level of our understanding of these sources and how to control them is not yet comparable to our knowledge of point sources. Current non-point source management plans, therefore, focus on continued research and planning efforts. Despite sophisticated research and planning by managers, the most effective current means of limiting and retaining runoff and decreasing land-based sources of nitrogen available for runoff transport can be achieved by individuals (Table 3).

Under the federally sponsored Long Island Sound Study, the states of Connecticut and New York, along with the U.S. Environmental Protection Agency, are developing management recommendations to reduce nutrient pollution to Long Island Sound. These recommendations represent four years of data collection and analysis and input from all of the entities that have management responsibility for the Sound. They will be released in a Comprehensive Conservation and Management Plan (CCMP), an important first step towards restoring the Long Island Sound. In reaction to public pressure however, New York, New Jersey, and the EPA have recently agreed to take advanced interim actions. Their "no net increase" policy will put a cap on nitrogen levels entering the Sound until the CCMP, possibly requiring a nitrogen reduction, is implemented.

CONCLUSION

The input of nutrients from New York City is stable or declining because the city's population is stable, its sewage treatment plants all will soon operate at a secondary treatment level, and a major abatement program is underway to reduce combined sewer overflow (CSO). In the CSO abatement program, holding tanks will be installed at sewage treatment plants to retain the excess mixed storm and septic drainage until, when excess flow has subsided, it can be redirected back to the plant for treatment.

The nutrient input from Long Island, Westchester County, and Connecticut is probably increasing along with increasing urbanization, as the population shifts from cities to suburbs, and increasing use of fertilizers and water in the Long Island Sound watershed. State programs, such as the Coastal Zone Management Programs and the Nonpoint Source Management Programs, working in parallel with the National Pollution Discharge Elimination System permitting program for stormwater runoff, and the national Clean Air Act, will aid managers in their efforts to curtail nonpoint source nutrients.

The most effective means of reducing any pollution problem is to reduce the input. Researchers are working to identify all possible mechanisms to reduce nonpoint nutrient input and to outline the best management practices to accomplish this. Similarly, "structural best management practices"--engineering solutions such as detention ponds in new housing developments--are being evaluated. But many structural solutions are expensive to install in developed areas. In these areas, individuals can play a major role by adopting the "best personal practices" for pollution control. ■

POSSIBLE FIELD TRIPS

1. Tour primary, secondary, and tertiary sewage treatment plants. Ask for information on the nutrient content of sewage entering the plants and for treated sewage leaving the plants.

2. Take a tour of a local aquarium. Inquire about the source of the water that is used in the tanks, the tank cleaning procedures, and the special chemical requirements of different organisms.

CLASSROOM ACTIVITIES

1. Based upon your visits to the sewage treatment plants and aquarium,

a) Compare the nutrient inputs and outputs at different sewage treatment plants. Plot the efficiency of nutrient removal on bar graphs.

b) Compare the chemical composition of treated sewage with the requirements of organisms at an aquarium. Discuss the possible consequences of discharging treated sewage into the marine environment.

2. Perform laboratory studies of the effects of plants and oxygen on marine or freshwater fish. Set up and compare the activities of fish in aquaria that are:

a) Aerated continuously and contain plants.
b) Aerated, but contain no plants.
c) Not aerated, but contain plants.
d) Not aerated and contain no plants.
e) Not aerated and contain a layer of mud or soil at the bottom.

3. Measure and plot the concentration of oxygen versus time in your laboratory aquaria experiments. Discuss the relationship between oxygen concentration and the activities of different types of fish.