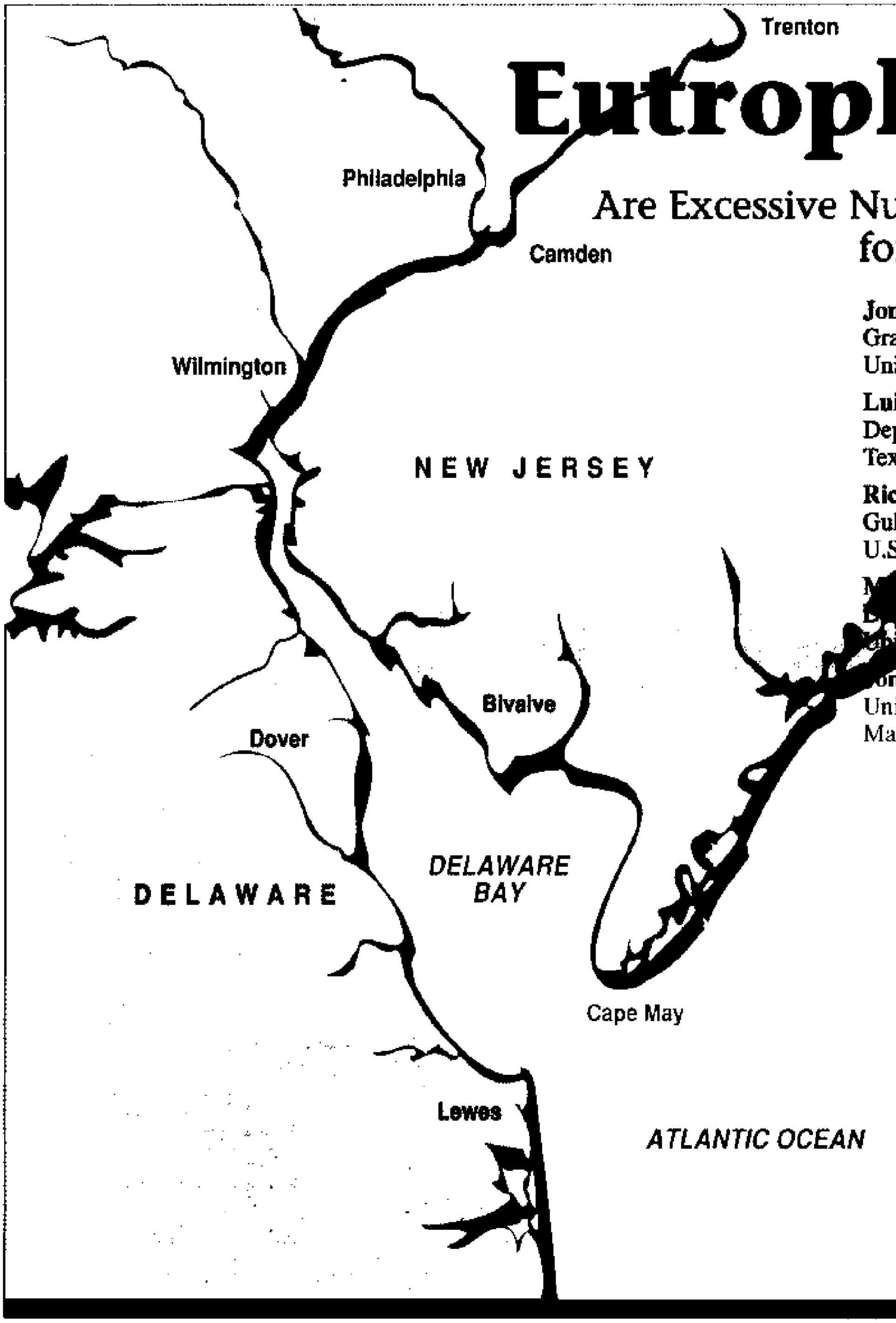
DELAWARE ESTUARY SITUATION REPORTS

This series of reports is devoted to discussion of current issues relevant to conservation, use, and development of Delaware Estuary resources, and of concern to managers, decision makers, and the general public.



The Delaware Estuary, a multi-purpose bistate resource.

Eutrophication

Are Excessive Nutrient Inputs a Problem for the Delaware Estuary?

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What Is Eutrophication?

The term eutrophic, from the Greek *eutrophos*, meaning "well-nourished," is used in aquatic ecology to denote a nutrient-rich or overfertilized condition. Eutrophication usually encompasses both the process of nutrient enrichment itself and a variety of ecosystem responses to nutrient inputs. Nutrient enrichment alone may not necessarily have a negative effect on aquatic ecosystems, but the enrichment frequently leads to excessive growth of microscopic algae. Excess algal material not consumed in the food chain may then be decomposed by bacteria, a process that depletes dissolved oxygen, especially in the bottom waters. Nutrient enrichment may also lead to undesirable changes in the number and variety of plant and animal species in the aquatic ecosystem. Most often, the use of the term eutrophication implies that one or more of these negative impacts have followed nutrient enrichment.

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The elements nitrogen (N) and phosphorus (P) are the primary nutrients that enrich many of the lakes, streams, rivers, estuaries, and coastal ocean waters of the world. Both are major components of most fertilizers. We mine the phosphorus concentrated in certain mineral deposits, extract nitrogen from the atmosphere, and than apply them to our high-density crops (including our lawns). Therefore, human activities such as agriculture, the collection and discharge of sewage, and, to a lesser extent, industry concentrate and redistribute both elements.

Moreover, human populations have congregated in areas where rivers meet the sea, due to our historical dependence on rivers for water-driven energy and on the sea for transportation. Hence, we have caused nutrient enrichment in most of the estuarine systems of the world. The Delaware Estuary is a relatively small river system with a very large population in its drainage basin. In fact, among U.S. estuaries, it is second only to the lower Hudson River in terms of population density in a drainage basin. Thus, the Delaware is a good candidate for severe eutrophication, but is it suffering from the negative consequences of nutrient overenrichment?

The Biological Role of Nitrogen and Phosphorus

In addition to human inputs, nutrients are introduced to estuarine ecosystems by the natural processes of weathering and erosion of rocks and soils by rainwater and the influx of seawater from the ocean. Estuarine plants at the base of the food chain use these dissolved nutrients to grow and reproduce until the supply of one or more nutrients is exhausted; that nutrient is then said to be *biolimiting*.

Nitrogen and phosphorus are essential for all life. Nitrogen is a building block of protein in all plants and animals. Phosphorus is less important structurally but crucial to energy-related processes within individual cells. Yet because both nitrogen and phosphorus in their biologically available forms are found in relatively sparse amounts in the Earth's overall chemistry and are only trace constituents of natural waters, they are the most frequent biolimiting elements. Dissolved inorganic phosphorus is present in a single form, phosphate (PO_4^{3-}). In contrast, dissolved inorganic nitrogen may take the form of ammonium (NH_4^+), nitrite (NO_2^-), or nitrate (NO_3^-). Nitrate is the most stable form of nitrogen in oxygenated estuarine waters and is said to be the fully *oxidized* form of this nutrient element. Figure 1 depicts the relationships between these forms of nitrogen in the aquatic nitrogen cycle.

Plants use nutrients, carbon dioxide, and energy from the sun to build new organic molecules and are thus referred to as *primary producers*. Producers in estuaries include emergent tidal plants, submerged aquatic vegetation, and large algae called macroalgae. However, in the Delaware Estuary, as in many estuaries, the most important producers are *phytoplankton* — microscopic, single-celled plants (algae) that float in the water.

Phytoplankton serve as the vital "first link" in the estuary's food chain, providing food for a wide variety of marine animals. Once phytoplankton take in nutrients from the water, those nutrients may be passed farther up the food chain as *zooplankton* (planktonic animals) feed on the phytoplankton, small fish feed on the zooplankton, larger fish feed on the small fish, and so on. However, with a very large supply of nutrients, phytoplankton have the capacity to overwhelm the food chain's ability to consume all of the primary production. Thus, the relationship of phytoplankton to nutrient inputs determines much of the biological productivity and richness of the estuarine ecosystem.

Defining the Delaware Estuary

To examine the historical trends and biological responses to nutrients in the Delaware Estuary, we need to define the boundaries of the environment. While the drainage basin of the Delaware River and Bay covers approximately 13,500 square miles in Delaware, New Jersey, Pennsylvania, and New York, the estuary is limited to the full tidal region from the head of tides adjacent to Trenton, NJ, to the mouth of the bay at the Atlantic Ocean.

Figure 2 shows the estuary with the distance axis established by the Delaware River Basin Commission (DRBC) converted to a kilometer (km) scale. A line drawn between Cape May, NJ, and Cape Henlopen, DE, becomes the zero point. The nonstraight axis then runs from that point up the middle of the shipping channel, through the urban region, to the head of tides. The broad lower bay narrows at around 70 km, and at 130 km the salinity gradient ends. So, from 130 km to the sea, a steady increase in salinity occurs, ranging from zero to about 30 parts per thousand. From 130 km (near Marcus Hook, PA) to 200 km is the tidal river region. Located at about 130 km is the routinely sampled DRBC station noted as "Marcus Hook." We have also used this location for routine sampling and have designated it the "zero-salt" location.

Eutrophication in the Delaware Estuary?

Some researchers have attempted to define eutrophication as a function of nutrient loading or concentration. *Nutrient loading* refers to the quantity of nutrients entering the system from a source or

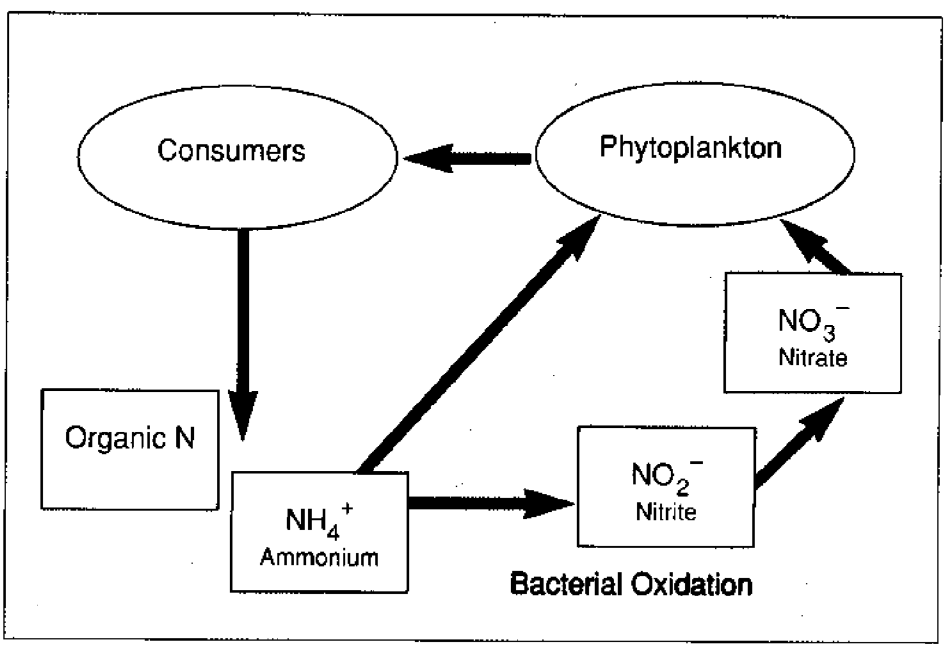

Figure 1. *A simplified view of the aquatic nitrogen cycle in which reduced nitrogen compounds (organic nitrogen, ammonium) are oxidized by bacterial activity, also called nitrification, through the intermediate of nitrite to nitrate. Plants (phytoplankton in aquatic systems) use either NH_4^+ or NO_3^- in photosynthesis and are consumed by small animals, which are consumed by larger animals. Eventually, nitrogen is returned to the water by consumers and decomposers.*

sources per unit time or area. Alternatively, *nutrient concentration* is the amount of nutrient (in terms of mass or number of atoms) present in a given volume of water. Nutrient loading is usually estimated for the entire estuary, while concentrations vary at different locations within the estuary. Reactions between a nutrient and other chemicals in the water at the nutrient's entry point, for example, may affect local concentration levels but not the overall nutrient load. In general, though, high nutrient loading leads to high nutrient concentrations in an estuary.

Several comparative evaluations of nutrient loading in estuaries and coastal waters have indicated that the Delaware Estuary has one of the heaviest loadings of nitrogen and phosphorus in the world. Among large estuaries and lakes, according to Jaworski (1981), the Delaware is second only to the Thames of England in nitrogen and phosphorus loading. In another evaluation (Nixon and Pilson 1983), the Delaware had the third highest nutrient loading in the United States, following New York's Raritan Bay and the South San Francisco Bay systems. By all accounts, the Delaware is one of the most nutrient-enriched estuaries in the United States and is considerably more nitrogen- and phosphorus-loaded than neighboring Chesapeake Bay.

But do the Delaware Estuary's heavy external nitrogen and phosphorus inputs make it eutrophic? Jaworski's scale of eutrophication (1981), based on nutrient loading, deems a phosphorus load of less than 1.0 gram/square meter/year (g/m^2/yr) to be below the level of excessive eutrophication. At 18.9 g/m^2/yr, the Delaware Estuary would definitely be considered eutrophic in these terms.

However, Ketchum (1969) used phosphate concentration rather than loading as an indication of estuarine eutrophication and also evaluated the algal *biomass*, or amount of algal material, resulting from phosphorus. With this approach, phosphate concentrations would have to exceed 0.05–0.09 milligrams of phosphorus per liter (mgP/l) for waters to be considered eutrophic. In the Delaware Estuary, the phosphate concentration ranges from 0.02 mgP/l at the mouth to 0.12 mgP/l near Philadelphia. Phosphate concentration, therefore, indicates only borderline eutrophication in the upper portions of the Delaware Estuary, where nutrients are most concentrated. The difference between the actual phosphate concentration and the concentration one would expect based on the Delaware's high rate of phosphorus loading is largely due to the geochemistry of phosphorus. Iron and manganese oxides in the water absorb excess phosphate, forming particulates that sink to the bottom. The phosphorus adsorbed onto suspended particles and in the sediments is slowly released to the water column to maintain phosphate concentration levels. As we shall see, though, with algal biomass as the determining factor, the Delaware Estuary should probably not be considered eutrophic at all.

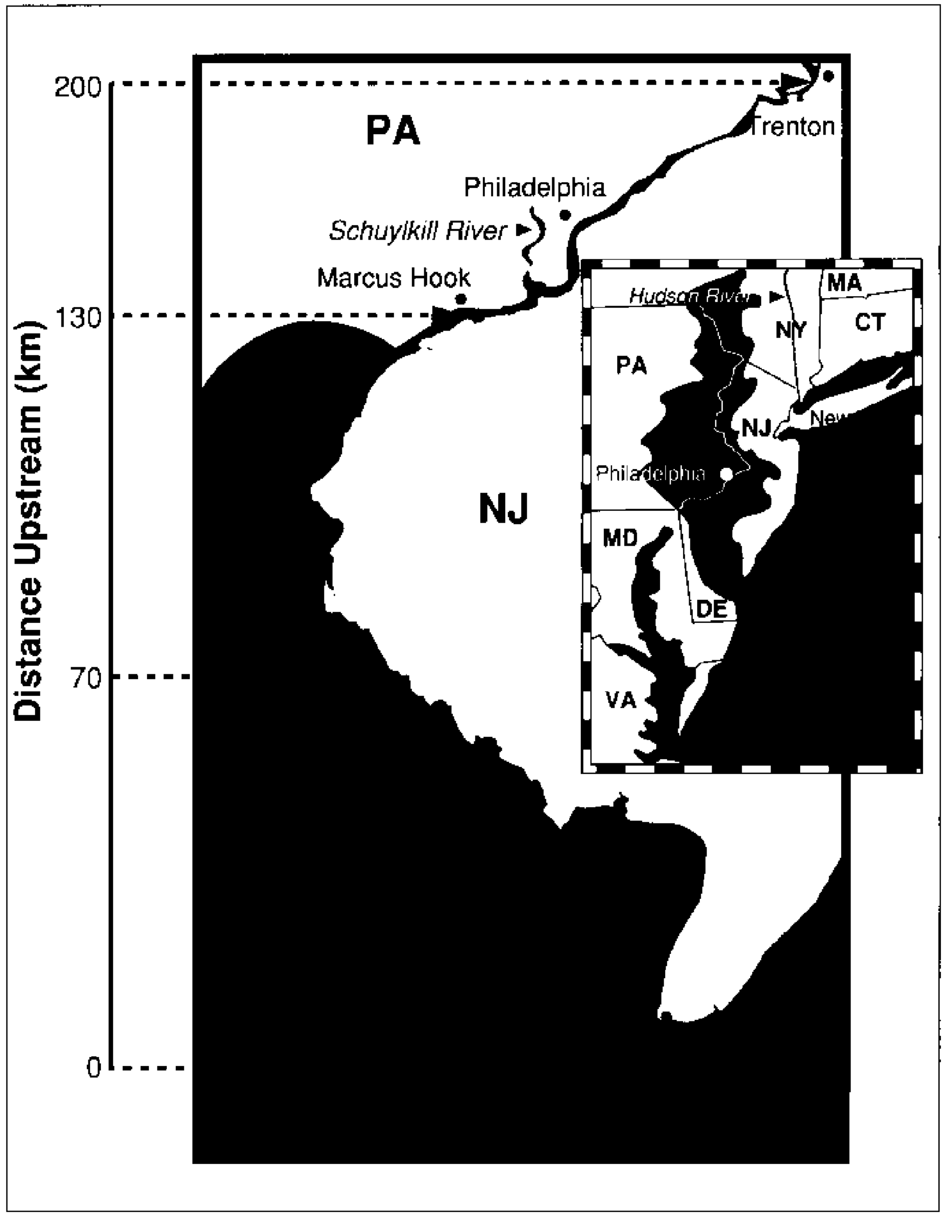

Figure 2. The Delaware Estuary with distances on a kilometer scale. Inset shows the entire drainage basin (shaded in black).

Present-Day Nutrient Distributions

The distribution of nutrients in the Delaware Estuary can be illustrated by plotting annual average concentrations along the axis of the bay, weighted in such a way as to eliminate the bias introduced by more frequent sampling during the warmer months of the year (Figures 3 and 4). Phosphate and nitrogen concentrations are lowest at the mouth of the estuary, while at the head of the tide, the two nutrients are elevated above "pristine" levels by diffuse land-runoff sources, including agricultural drainage, and also by some municipal and industrial inputs in the upper part of the drainage basin. Throughout the urban region of the estuary, there are also diffuse land-runoff inputs and significant inputs from industry. However, the greatest inputs by far are from five large municipal sewage treatment plants in the Philadelphia/Camden/Chester area.

Figure 3 shows the distribution of phosphate concentrations. The concentration at the head of the tide (about 200 km) is moderately high and, without additional

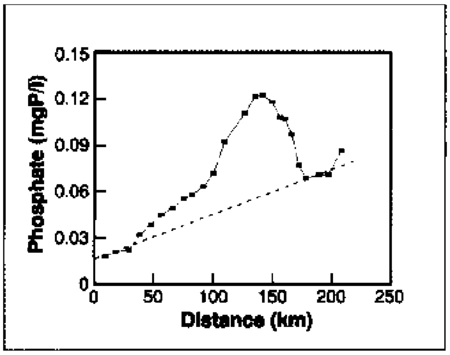

Figure 3. Concentrations of dissolved phosphate along the length of the Delaware Estuary. The dashed line indicates how phosphate concentration might be expected to decrease without additional inputs in the urban region of the estuary. The data are averaged from weighted monthly measurements for a one-year period in 1986–87. The distance in kilometers is from the mouth of the estuary at zero to the head of the tide at 200.

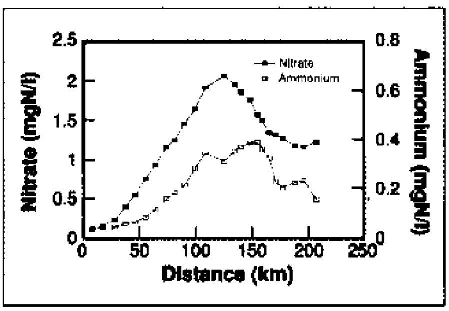

Figure 4. Concentrations of dissolved nitrogen species (nitrate and ammonium) along the length of the Delaware Estuary. The data are averaged from weighted monthly measurements for a one-year period in 1986–87. Note the different scales for nitrate and ammonium.

inputs, could be expected to decrease regularly by dilution going toward the sea (dashed line). This moderately high level is what one might expect of a temperate river with some enhancement from agricultural runoff. The very large increase in phosphate peaking at about 140 km is from the sewage effluents in the Philadelphia region.

Figure 4 shows a similar distribution picture for the nitrogen compounds, nitrate and ammonium. Nitrate, the stable, less reactive form to which all dissolved nitrogen is eventually oxidized is predominant. It has a distribution similar to that of phosphate but peaks at about 130 km, a shift downstream from the phosphate peak. The reason for this downstream shift is that ammonium, the major component of sewage effluents, is gradually oxidized to nitrate by bacteria through a process called *nitrification* (Figure 1). The ammonium distribution in Figure 4 shows a peak closer to the location of the phosphate peak at 140 km. Clearly, sewage effluents in the Philadelphia area have a profound impact on the estuary.

The Role of Dissolved Oxygen

In aquatic environments, microbes use dissolved oxygen as they break down organic matter and convert ammonium to nitrate. In response to direct human inputs of ammonium and organic matter (e.g., sewage sludge or some industrial wastes), the microbes' need for oxygen can be great enough to push dissolved oxygen levels very low. This microbial, mostly bacterial, use of dissolved oxygen is called *primary biochemical oxygen demand (BOD)*. In addition, when elevated nutrient concentrations stimulate excess algal production under the right conditions, bacteria may degrade the excess organic matter produced, consuming dissolved oxygen in the process. This indirect result of human inputs is often referred to as *secondary BOD*.

The Delaware Estuary has had a very serious dissolved oxygen depletion problem, dating back more than a century. Dissolved oxygen concentrations in the tidal river were once some of the lowest seen in any U.S. estuary; however, it was largely a primary BOD problem due to effluents high in organic matter and ammonium. The excessive algal blooms that can cause secondary BOD have not been observed in the Delaware Estuary.

The Delaware has since undergone a very successful cleanup resulting in much higher dissolved oxygen levels today than were present a few decades ago (Albert 1988a). Figure 5 documents the improvement of dissolved oxygen in the Delaware Estuary. The data for this figure were averaged over an annual basis from seasonal ranges. An obvious feature is the large "oxygen sag" in the urban region. In the late 1960s, the sag was so pronounced that even the higher winter concentrations did not bring up the annual average. By the early 1980s, improvements in industrial effluents and some municipal effluents had somewhat lessened the dissolved oxygen sag. But not until the late 1980s did ever more successful sewage treatment almost remove the sag.

Seasonal fluctuations in dissolved oxygen can be seen in Figure 6, which shows monthly averages from DRBC samples

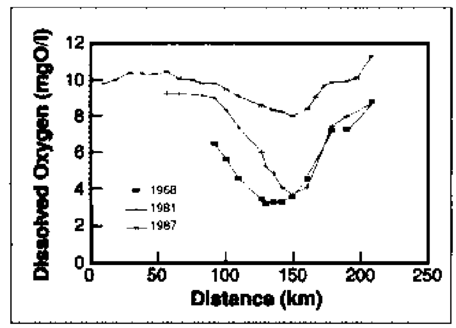

Figure 5. Dissolved oxygen concentrations in the Delaware Estuary. Each line of concentration represents an annual average from weighted monthly intervals. The data for the first two curves (1968, 1981) were collected by the Delaware River Basin Commission (DRBC).

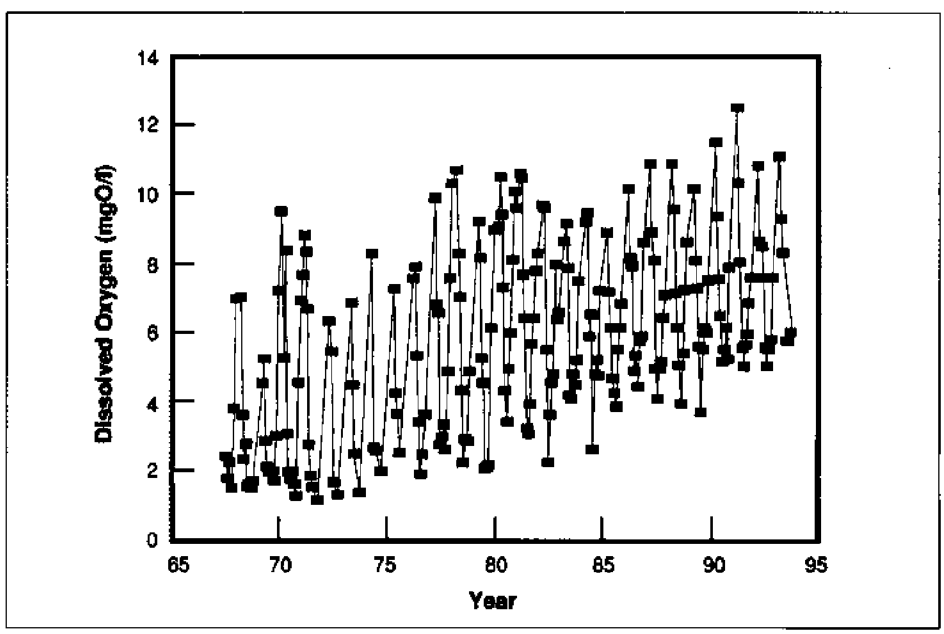

Figure 6. Seasonal variation in dissolved oxygen concentration at the zero-salt location (about 130 km from the mouth) in the Delaware Estuary. Lowest values are from summer sampling; highest values are from winter sampling. Data collected by DRBC.

taken at the Marcus Hook/zero-salt location, the low point of the old oxygen sag. Dissolved oxygen concentrations are lowest in the summer when the BOD is greatest and warm temperatures decrease the amount of oxygen the water will hold. The maximum oxygen levels during the winter now exceed 11 mgO/l as opposed to past measurements below 8 mgO/l. Summer minima are now above 5 mgO/l in contrast to the monthly average values of the late 1960s, which were consistently less than 2 mgO/l. As you can see, dissolved oxygen concentrations have improved greatly in recent years. However, neither now nor in the past was the low-dissolved-oxygen phenomenon the result of excessive algal growth.

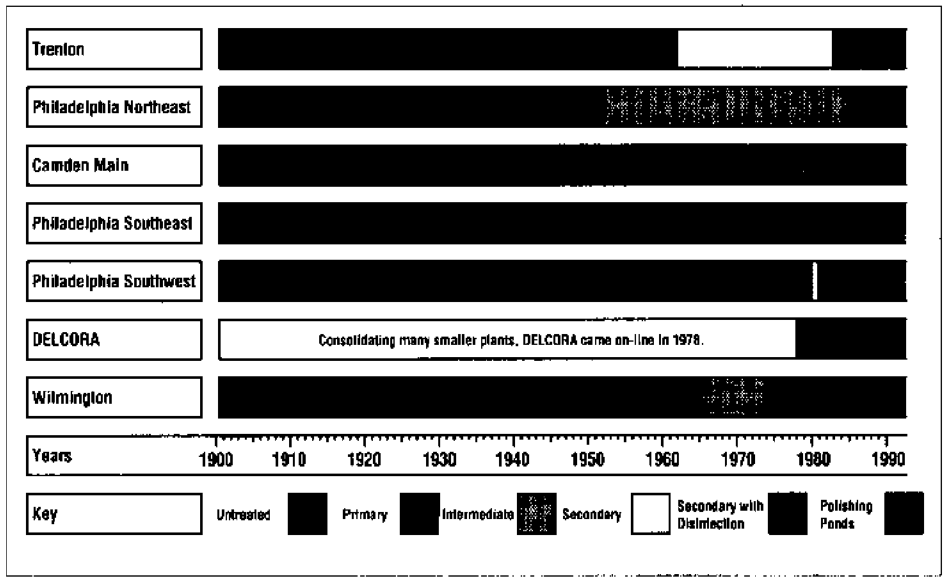

Figure 7. History of treatment in the major municipal sewage plants in the urban region of the Delaware Estuary. (Figure from Albert 1988b.)

Historical Trends of Nutrients in the Delaware Estuary

While sewage effluents from the most populous area in the drainage basin still make extremely large contributions of nutrients to the Delaware Estuary, their impact was once even greater. According to one report, Philadelphia alone discharged 350 million gallons of raw sewage into the river each day in the 1940s (Albert 1988b). Although these municipal inputs resulted in well-documented environmental degradation, which reached its peak in the mid-1900s, little is known about actual nutrient concentrations during this time because of insufficient sampling.

The sewage treatment plants in the Philadelphia area have undergone extensive upgrades since 1980 so that the BOD from their effluents is far lower than that of earlier decades. Figure 7 shows a time line of recent improvements in these five plants, plus the Trenton and Wilmington sewage treatment plants. The improvements in sewage treatment, and the resulting decrease in BOD, led directly to the improved dissolved oxygen levels shown in Figures 5 and 6.

One reason for the lower BOD is the decreased concentration of ammonium in the effluents. As previously mentioned, bacterial nitrification converts ammonium to nitrate using dissolved oxygen. The new generation of sewage treatment facilities maintains higher dissolved oxygen levels in the estuary by allowing much of this conversion of ammonium to nitrate to take place before the effluents are discharged. As shown in Figure 4, nitrification of the remaining ammonium continues as it is moved downstream, further reducing ammonium levels. The winter high values for ammonium used to be about 2 mgN/l and are now about 0.5 mgN/l (Figure 8). Summer lows have dropped from about 0.5 mgN/l to near zero. However, since the dissolved inorganic nitrogen in sewage is only oxidized and not removed in sewage treatment, this large decrease in ammonium does not translate to a large decrease in total nitrogen when nitrate, nitrite, and ammonium are combined, as shown in Figure 9. Historically, total nitrogen ranged from about 2 to 4 mgN/l. Today, the range is about 1.5 to 3 mgN/l.

The long-term record for total phosphorus is somewhat different from the nitrogen record. A drop in total phosphorus concentrations (which include particulate phosphorus and dissolved organic phosphorus as well as the phosphate ion) since the 1960s appears to reflect a decline primarily in seasonal high levels. There are no good, long-term historical records for the dissolved phosphate ion as a fraction of the total phosphorus pool. It has not been as readily monitored as nitrogen. However, since the early 1980s, we have seen an increase for the phosphate ion alone (Lebo and Sharp 1993).

Thus, the overall trend in recent years does not show a large drop in nutrients in the Delaware Estuary system. The large decline in ammonium nitrogen has been partially offset by increases in nitrate, resulting in only small declines in total dissolved inorganic nitrogen. Winter high values for total phosphorus have declined considerably, but concentrations the rest of the year are similar today to those of one or two decades ago. Therefore, because there have been only small changes in nutrient levels, we would not expect to see a dramatic change in the algal response to those nutrients.

Biological Responses in the Delaware Estuary

The very high present-day nutrient levels in the tidal river and at the upper end of the salinity gradient should provide sufficient enrichment to support excessive algal production. However, algal production in the Delaware is comparable to most major estuaries rather than exceptional. Figure 10 shows primary production of phytoplankton along seasonal transects up the estuary. This figure reveals that the level of primary production (measured by tracing the uptake of carbon in a water sample) is not very high. We have documented this both in terms of phytoplankton biomass (Pennock 1985) and primary production (Pennock and Sharp 1986). The highest production occurs in the lower estuary, with much lower levels in the urban region where nutrient concentrations are highest.

Figure 10 also shows average annual suspended sediments in the Delaware Estuary (shaded area). There is a maximum of suspended particles, or *seston*, at 100 km, which is the area of maximal resuspension of bottom sediments due to the action of the tides (Biggs et al. 1983). The turbidity at this point is so high that very little light penetrates the water, severely limiting algal production. Downstream, as the water becomes clearer, primary production increases, reaching a maximum spring bloom at about 30–60 km and a summer maximum near the mouth of the estuary (Figure 10).

What is most remarkable is that in the region of about 130–160 km, where the water is both fairly clear and very high in nutrients, primary production is low. Both

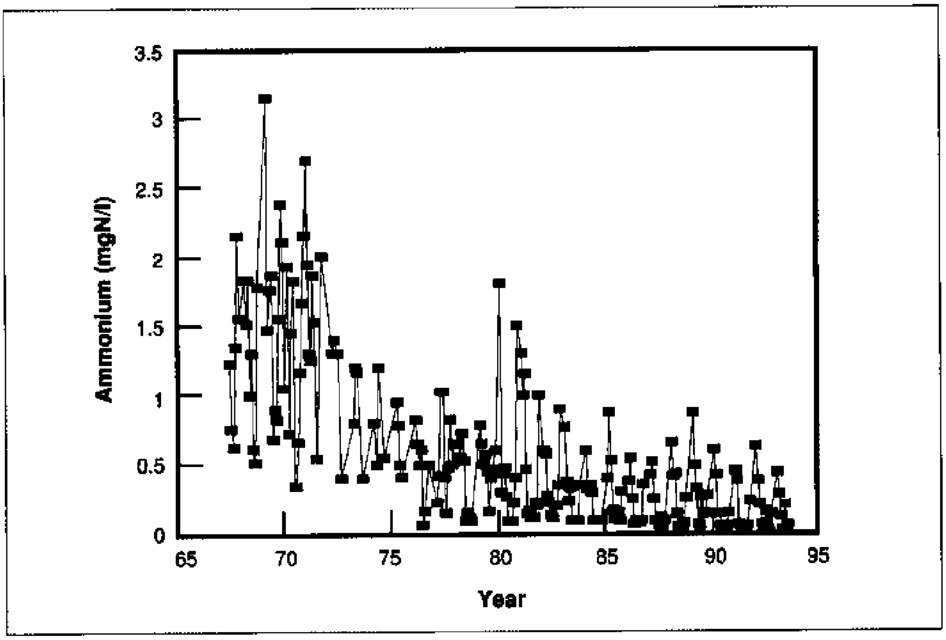

Figure 8. *Ammonium concentration over time at the zero-salt location (130 km) in the Delaware Estuary. Lowest values are from summer sampling. Data collected by DRBC.*

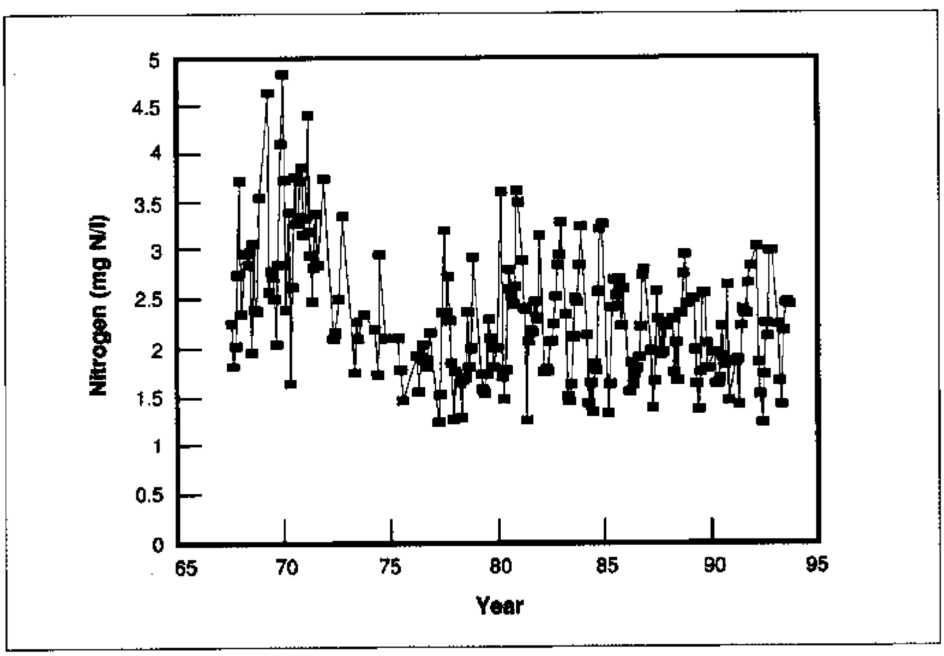

Figure 9. *Total available dissolved inorganic nitrogen (nitrate, nitrite, and ammonium) at the zero-salt location in the Delaware Estuary. Data collected by DRBC.*

in the spring, when there is a pronounced bloom in the lower estuary, and in the fall, when the level of production in the lower estuary is still high, production is very low in the river. Only in the summer is production elevated in the tidal river, and even then, it is not very high. In addition, the riverine summer production maximum is upstream of the nutrient maximum and drops in the region of highest nutrient levels. There is some indication, but no firm evidence, of potential toxic effects influencing the phytoplankton in this region (Sanders and Riedel 1993). It appears that something depresses the riverine primary production, but we cannot fully explain it at this time.

The overall picture, then, is one of strongly light-limited primary production in the region of the turbidity maximum; highest (but not excessive) production in the clearer, lower estuary; and much reduced production in the clearer and highly nutrient-enriched tidal fresh waters. While at present we cannot completely explain the low production in the tidal river, we can explain much of what happens to nutrients as they move through the estuary.

The Fate of Nutrients in the Delaware Estuary

Most chemical elements occur in more than one form, or *isotope*, but usually only one of them commonly occurs in nature. Using the relative natural abundances of the common and rare isotopes of carbon and nitrogen, the uptake by phytoplankton of isotopically tagged nitrogen and phosphorus and advection-dispersion modeling, we have been able to follow the use and transport of nutrients in the Delaware Estuary. The very high nutrient inputs in the urban region of the estuary are largely transported, or *advected*, downstream and diluted. In a simplified picture, the major pathway taken by nutrients begins with uptake for primary production by phytoplankton, followed by the use of the phytoplankton in the food chain, and the eventual regeneration by microbes. *Regeneration* refers to the return of nutrients directly to the water through excretion at all steps in the food chain and microbial processing of wastes.

Ammonium is highest during the winter when bacterial nitrification is lowest (Cifuentes et al. 1989), and this ammonium is transported downstream (Cifuentes et al. 1988). In the beginning of the spring bloom, this advected ammonium is the principal nitrogen source for phytoplankton (Pennock 1987). Toward the end of the spring bloom, the ammonium supply is exhausted (Sharp et al. 1986), and phytoplankton switch to advected nitrate as their source of nitrogen (Pennock 1987). The spring bloom terminates when phosphate is also exhausted (Lebo 1990; Lebo and Sharp 1993).

Summer primary production is supported by locally regenerated ammonium (Cifuentes et al. 1989) and phosphate (Lebo and Sharp 1992). The majority of the organic matter in the lower estuary comes from *in situ* production as opposed to riverine advection or marsh exchange (Cifuentes 1991). Bacteria in the estuary are most abundant and productive in the lower estuary (Coffin 1989). The bacteria appear to be tightly linked to phytoplankton production in the summer, but not in the spring when there is little nutrient regeneration (Coffin and Sharp 1987).

It appears that much of the nitrogen and phosphorus input into the urban river is exported from the estuary as a result of this nutrient-phytoplankton-bacteria pattern. A large amount of nitrogen probably leaves the estuary as dissolved nitrate (Cifuentes et al. 1990), and much of the phosphorus probably leaves as particulate matter (Lebo and Sharp 1992). Overall, not only is the high nutrient input not responsible for eutrophication (excess algal production) in the Delaware Estuary, but much of the input exits the estuary entirely to the adjacent continental shelf. There may therefore be reason for concern about the eutrophication of the coastal waters.

Regulations and the Future

Efforts to improve dissolved oxygen levels during the 1980s clearly benefited the Delaware Estuary and its living resources. A dramatic example is the comeback of the American shad. Once blocked from their upstream spawning grounds by the lack of oxygen in the Philadelphia vicinity, their numbers have been on the rebound since dissolved oxygen levels in the upper estuary were restored in the late 1980s. There is still some demand for oxygen to oxidize ammonium, and overall dissolved oxygen levels are periodically below water-quality standards. Further improvements are still needed and are within the scope of the Delaware River Basin Commission's plans.

Overall nutrient levels in the Delaware Estuary remain high. Yet despite the fact that all the necessary conditions for eutrophication exist in the estuary, the negative impacts of nutrient enrichment appear to be absent. And since the estuary's high nutrient levels do not cause a major problem today, it is not clear that further efforts to decrease nutrient levels in the Delaware Estuary via government regulations would result in a corresponding improvement in the health of the estuarine ecosystem.

Up to now, discussion of such restrictions has generally applied to municipal and industrial outflows, often referred to as *point sources* of nutrients since their precise locations are usually known. Recently, *nonpoint sources* of nutrients such as agricultural and residential runoff emanating from diffuse sources throughout the drainage area, have also been targeted. Compared to sewage effluents in the Philadelphia metropolitan area, however, nonpoint sources are minor inputs. As a result, there are no regulations mandating nutrient reductions on an estuary-wide basis, and all indications are that none are needed at this time. There is some valid concern about nonpoint-source inputs of toxic chemicals. This is an issue separate from that of nutrients and one requiring further action.

This perspective is on the Delaware Estuary as a single large system. Local nonpoint-source nutrient inputs to tributaries of the Delaware Estuary system can be a different issue. Therefore, the need for nonpoint-source nutrient reduction should be evaluated on a local level, and in many cases, such reductions are probably justified. Also, there is a need to consider whether transport of nutrients through the estuary to coastal waters creates a serious coastal nutrient enrichment problem.

The Delaware Estuary Program, a cooperative local, state, and federal program charged with preparing a comprehensive conservation and management plan for the estuary, is not proposing any specific action plans for large-scale nutrient reduction, but there is considerable concern about nonpoint-source inputs in general and about land-use planning to prevent such inputs. The evaluation here is in no way inconsistent with such concerns. Furthermore, concerned individuals who live within the estuary's drainage area can voluntarily contribute to the estuary's health by recalling the ultimate destination of municipal wastewater and storm drainage and making appropriate lawn-maintenance and water-use decisions.

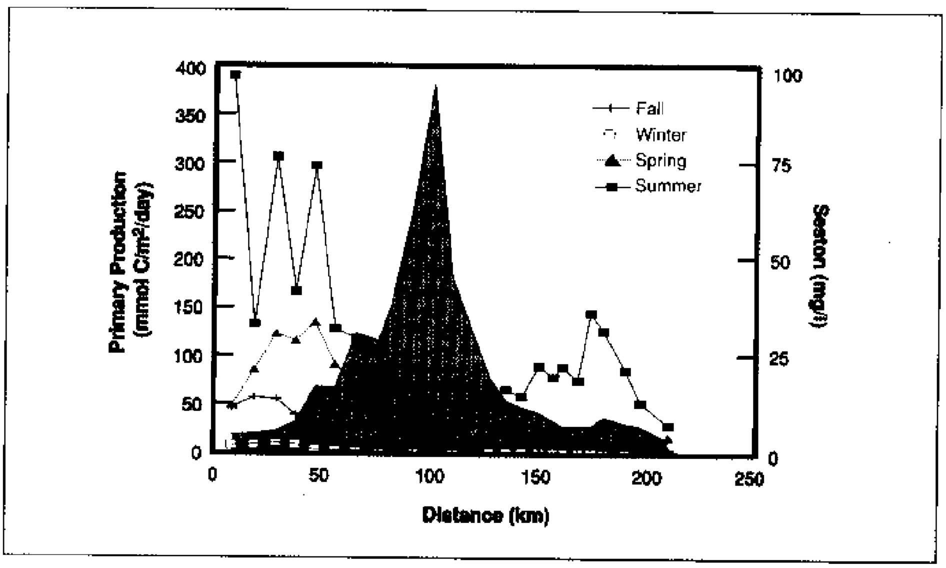

Figure 10. *Seasonal primary production along the length of the Delaware Estuary. Production data are estimates from carbon 14 (^{14}C) measurements integrated over depth and taken for a one-year period in 1986–87. Suspended sediments (seston) along the length axis of the Delaware Estuary are represented by the shaded area; data are from weighted monthly measurements for a one-year period in 1986–87.*

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