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Dispersal Pathways for Particle-Associated Pollutants

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Dumping of anthropogenic wastes into the ocean is a practice that presumably extends as far back in time as the origin of coastal cities. However, the effects of this practice have been under systematic study only since the advent in the 1970's of enhanced environmental awareness. A prototype study in the United States has been the New York Bight Program of the National Oceanic and Atmospheric Administration.

Summary. Particle-associated pollutants (totaling 10^7 metric tons per year) are introduced into the New York Bight by ocean dumping, estuarine discharge, sewage outfalls, eolian transport, and shipping waste and spillage. Oceanic and estuarine circulation processes dilute and transport the particles by a natural dispersal system that also tends to be highly distributive; particle-associated pollutants apparently seek the same sinks in the Hudson River shelf valley and intracoastal wetlands, regardless of their point of introduction.

Solid wastes from some 20 million people, totaling about 9.8×10^6 metric tons (*1*), are discharged each year into the New York Bight (Fig. 1). While ocean dumping is the most important source, wastes also arrive through sewer outfalls, eolian transport, river discharge, land runoff, and vessel wastes and spills. The wastes dumped include sewage sludge, dredge material, acid waste, and construction and demolition debris (cellar dirt) (*1*). A review of chemical pollutants of the New York Bight (2) has concluded that the major perceived threats are from chlorinated pesticides, lead, mercury, polynuclear aromatic hydrocarbons, polychlorinated biphenyls, and plutonium (*2*). Dredge material contributes the major part of the input (24 to 60 percent) of cadmium, chromium, copper, iron, lead, and zinc (*1*). Wastewater contributes 70 percent of the mercury; wastewater and runoff also contribute organic carbon, nitrogen, phosphorus, and the microbial load (*1*). Various effects of contaminants have been reported within the New York Bight apex (*1*, *2*). Recent crises that attracted public attention were the sewage sludge scare of the summer of 1974 (*3*), contamination of Long Island beaches by floatables in the summer of 1976 (*4*), and the anoxia-induced fish kills of 1976 (*5*).

Because pollutants are associated with fine sediment particles, their fate in the New York Bight is intimately related to sediment transport processes. Progress has been made toward understanding and, to some extent, quantifying processes that affect fine sediment dispersal in the inner bight. The dynamics of the more typical sandy substrate in the bight, which acts as both storage matrix and depositional surface for the fine sediments, has been described (*6*).

Modeling the Fine-Particle Transport Regime

Generally, Atlantic shelf water flows along contour southward through the New York Bight at an average rate of 2 to 4 cm/sec. The flux of seawater through the entire Middle Atlantic Bight is on the order of 8000 km^3 per year; for a volume of about 6000 km^3, this flux gives a mean residence time for a water particle of about 9 months (*7*). This alongshelf flow is joined by freshwater runoff (flux, 0.8 km^3 per year) from the Hudson-Raritan river system. Analysis of 2200 days of current meter records (*8*) shows that fluctuations in speed and direction are superimposed on this slow southward drift by the passage of mid-latitude, low-pressure storm systems at 3- to 10-day intervals. During more intense storms, mid-depth velocities as high as 40 cm/sec have been sustained for several days (*7*). Water mass excursions of many tens of kilometers paralleling the coastline may occur during storms, suggesting that long observation periods are needed to determine the residual circulation pattern.

Sediment transport in the New York Bight is not a simple function of fluid transport. In most areas of the open shelf, threshold erosion velocities for the sandy substrate, ranging from 12 to 40 cm/sec, are only exceeded by the steady component of flow for relatively short periods during storms. Wind-generated surface waves also superimpose a high-frequency oscillatory flow on the steady bottom flow. Bottom stresses due to the nonlinear combination of steady and oscillatory currents during storms may greatly amplify transport of particulates near the bottom. Consequently, a combined flow boundary layer model was developed to improve near-bottom sediment transport predictions, and semiempirical relations were derived to predict resuspension of the small amounts of

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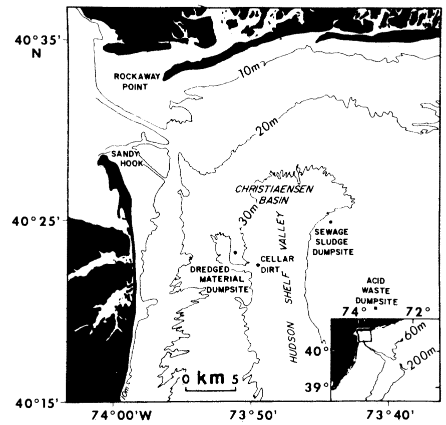


Fig. 1. Apex area of the New York Bight. (Inset) The New York Bight in relation to the Atlantic continental shelf of the northeastern United States.

pollutant-bearing mud dispersed in the sand-dominated substrate (*9*).

The main focus of mud deposition is in the Christiaensen Basin and Hudson Shelf Valley (Fig. 1). Minor mud patches occur off shore in local small depressions and near lagoon inlets close to shore (*10*). Fine sediments typically constitute 5 percent or less of the surrounding sandy substrate (*10*). The suspended sediment concentration field has a relatively simple structure. Most suspended sediment is carried in a turbid, near-bottom nepheloid layer several meters thick and, to a lesser extent, in a near-surface layer within the photic zone (*11*). Mud particles are repeatedly cycled through this bottom nepheloid layer and remain suspended in it for hours or days before eventual burial, ingestion, or diagenesis. Off shore, nepheloid layer concentrations range between 0.5 and 1.0 mg per liter in the winter to 0.05 and 0.005 mg per liter in the summer. Within about 1 km of the beach, near-bottom particle concentrations are generally greater by a factor of 10. Storms increase near-bottom values by a factor of 10 to 100 and those in the upper water column by as much as a factor of 10, depending on the depth of the water column, water stratification, and the type of sediment.

The intermittent and often nonlinear nature of fluid and fine sediment transport suggests that the transport of sediments in the New York Bight can be modeled as a random walk or diffusion process (*12*). In our model, the semidiurnal tidal component of flow is seen as a deterministic transporting agent that, in the absence of other processes, would result in little net movement of sediment. Randomly occurring, wind-driven storm flow events constitute probabilistic resuspension and advection elements of the model. Historical wind, wave, and current data are used to determine sediment diffusion and advection coefficients at the vertices of a grid encompassing the New York Bight.

A vector map of the advection coefficient reveals a southwesterly bias in sediment transport as a consequence of the preferred southwesterly trend of storm flows (*7, 8*). The model also indicates (Fig. 2) that particles introduced at the dump sites and dispersed by the natural tranport system ultimately impinge on the Long Island and New Jersey nearshore areas, but only in very small quantities and after relatively long times following dumping (*12*). While these modeling studies have led to a better understanding of the long-term time scales for particle-associated pollutant dispersal, they do not adequately address the important relation between sources of and sinks for particle-associated pollutants.

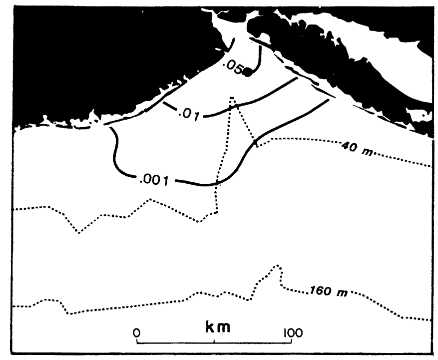


Fig. 2. Distribution of mud (percentage by weight) in sandy bottom sediments predicted by a numerical model (*12*) after 40 years of dispersion from the present (1978) dredge material location (dot in apex) by typical tides, waves, and storm and shelf currents.

Particle Dispersal Budgets

An initial mass budget has been proposed for the particle dispersal system in the New York Bight, wherein the major transport pathways among sources and sinks have been identified and their associated flux rates estimated (*13*). Some of the more significant errors in our budget have also been estimated, but it is not always possible to evaluate them quantitatively.

The sediment budget (Fig. 3) is that of a highly dispersive transport system. Many of the pathways shown are two-way pathways, in which net transport is only a small fraction of the total value. The diffusive behavior of the fine sediments suggests that a pollutant introduced into any part of the system will eventually be dispersed throughout the system before undergoing permanent deposition at a preferred site.

The Hudson-Raritan estuary plays an important role in the particle mass budget because it can act as both source and sink for particles in the bight apex. Depositional sinks within the estuaries and lagoons include tidal flats and marshes (Fig. 3), wherein mechanisms such as the scour and settling-lag effect and the time-varying asymmetry of tidal flows induce particles to migrate landward and to undergo final deposition there (*14, 15*).

Dilution of river sediment by marine sediment appears to be characteristic of mid-latitude, temperate-zone estuaries whenever the provenance of their sediments has been examined in detail, and there is evidence for net landward transport and accumulation of fine sediments within most estuaries along the east coast (*15*). In a recent study, Olsen and co-workers (*16*) used ^{14}C ages in sediment cores to show that 1.5×10^6 metric tons of fine-grained particles accumulate per year in the upper Hudson River estuary. Relative activities of anthropogenic uranium nuclides in the fine-particle load suggest (*16*) that 60 to 70 percent is derived from rivers, 10 percent is derived from sewage solids and in situ productivity, and 15 to 20 percent is of marine origin. Our study does not extend to the lower estuary, but, by analogy with similar estuaries (*15*), we expect ocean-derived sediment to dominate over river-derived sediment in that area.

The Hudson-Raritan estuary also acts as a source for particle-associated pollutants to the bight apex through the tidally induced, twice-daily exchange of estuarine and ocean waters through the mouth of the estuary. Studies of the mass transfer rates between the bight apex and the estuary (*13, 17*) indicate that particle mass flux during ebb and flood tidal phases is approximately equal, averaging about 20×10^6 metric tons per year. The net flux is difficult to estimate because the data sets for tidal flow and suspended particle concentration are not synoptic and also because they do not resolve the brief, high-volume transport events associated with storms. An error analysis performed on the data yields a conservative estimate of net flux into the estuary of about 0.4×10^6 metric tons per year, which may be underestimated by a factor of 2 to 4 (*13*). However, the largest source of estuarine sediment to the bight apex is still dumped dredge material (*1, 13*)(Fig. 3).

Alongshore transport into the bight apex, the other major source of suspended particles, is on the order of 1.3×10^6 metric tons per year (*13*). Like estuarine flux, the alongshore net particle flux is also difficult to quantify accurately because fully synoptic flow and particle data are not available. Analysis of the biasing effect due to temporal undersampling (failure to include storms) suggests that the net along-coast flux may be underestimated by a factor of 2 to 4 (*13*). Thus the sum of the sediment inputs to the New York Bight apex (from upcoast, sea floor erosion, natural erosion from fringing marshes and older deposits, and biological productivity) is estimated to be at least equal to, and probably greater than, the combined anthropogenic flux to the sea floor and water column from dumping (Fig. 3).

The dispersive characteristics of the bight apex are also illustrated by some simple calculations of residence time. The water mass of the New York Bight apex is exchanged every 4 to 12 days (*7*). The average residence time, T, of a suspended sediment particle in that water mass is m/i, where m is the mean total suspended load in the bight apex and i is the mean input rate. The mean suspended load of the bight apex is estimated to be 57×10^3 metric tons (*17*). If we consider only the input (Fig. 3) from eolian transport, along-shelf transport, lagoonal discharge, and sea floor erosion (2.3×10^6 metric tons per year, equal to 6.3×10^3 metric tons per day), then T is about 9 days, which is comparable to the duration of the exchange period. Such rapid mixing must serve to homogenize, but not to concentrate, particle-associated pollutants because the results of our dispersion modeling suggest that many tens of years are necessary for trace amounts of particles introduced at dump sites to reach the nearshore areas.

Particle-Associated Pollutant Dispersal Patterns

The distribution patterns of adsorbed chemical species within the bottom sediments are time-averaged responses to the prevailing sediment transport processes and consequently provide at least a qualitative test of the budget and transport models. The sterol coprostanol is an especially useful tracer of sewage sludge because it is produced exclusively in the mammalian gut. Earlier measurements of the coprostanol content in fine bottom sediments in the bight apex revealed that the highest concentrations were in the muddy Christiaensen Basin, adjacent to the sewage sludge dump site (*18*). Subsequent sampling during our studies, over a broader area and with a more sensitive analytical procedure, again yielded relatively high values in the mud-accumulating Christiaensen Basin (12 percent by weight of total sterols), but values that are as high or higher (ranging from 8 to 31 percent) occur over the length of the intracoastal zone (Fig. 4).

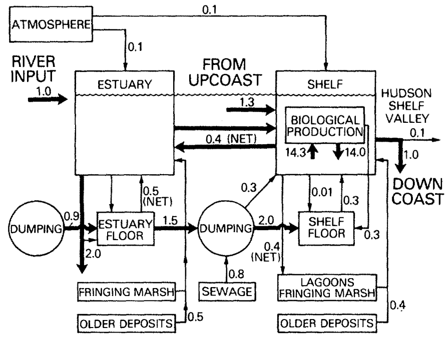


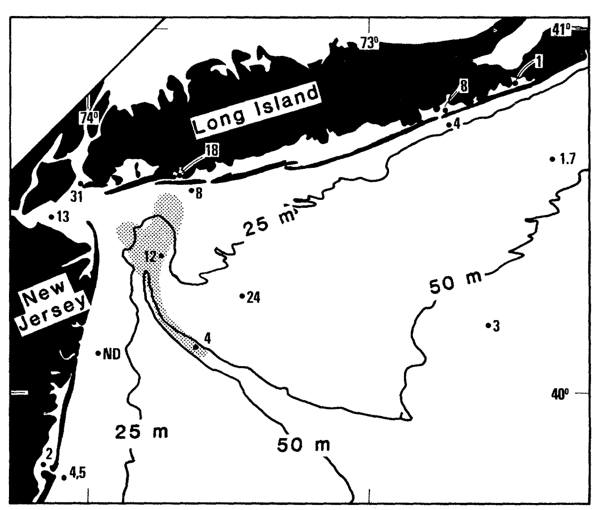
Fig. 3. Fine-sediment budget model for the New York Bight apex, Hudson-Raritan estuary system. Values are in metric tons $\times 10^6$. [Modified from (*13*)]

The distribution pattern of coprostanol suggests that the use of weight ratios has not entirely eliminated the effect of grain size; the finer muds of the intracoastal zone generally contain more adsorbed coprostanol in their sterol fraction than do the coarser silt and mud particles of the open shelf. If the offshore sewage sludge dump site were the sole source for coprostanol in the bight apex, then coprostanol would have to bypass the inner shelf from the dump site to reach the intracoastal zone. However, not all the sewage sludge in the bight apex comes from the dump site; large quantities of untreated sludge are also released within New York Harbor and by outfalls from Long Island and New Jersey municipalities (*2*). We note that 31 percent of the total sterols at Norton Point in the Hudson estuary (Fig. 4) was coprostanol; this is the same value reported for raw sewage (*18*). In any case, the coprostanol sewage-sludge indicator occurs wherever mud is being deposited in the bight apex, a pattern indicating a highly dispersive system.

Trace metal patterns in bottom sediments, like patterns for organic constituents, appear to reflect both an offshore waste disposal source and input from the Hudson estuary. In this case, the principal mechanism appears to be dumping of dredge material rather than sewage sludge. Dredge material dumped in the bight apex includes material from metal-contaminated sectors of the estuary floor. Data from an analysis of a "metal stratigraphy" in cores from the dredge material dump site, in which selected strata are enriched in iron, manganese, lead, copper, silver, cadmium, and mercury, suggest that the dump site sediments are considerably enriched in these metals with respect to underlying deposits and that the enrichment is equal to or greater than that reported for other water bodies affected by industrialization (*19*). Those enrichment estimates, however, are not normalized for sediment grain size, and, since muddy dredge material was compared with coarse sediment, the estimates are almost certainly too high.

The mass of selected metals associated with dumped dredged material from 1973 to 1978 has been compared with the total mass of metals found in sediments at the dump site (*19*). Accumulations at the dump site during this period varied from 0.5×10^2 metric tons for cadmium to 0.63×10^6 metric tons for iron. Approximately 53 and 58 percent of the iron and manganese, respectively, remains; other metals exhibit much greater losses. Here, sedimentary pore waters are enriched in iron, manganese, and zinc, and a halo of dissolved manganese and cadmium has been observed in near-bottom waters adjacent to the dump site. Calcu-

Fig. 4. Coprostanol (dot) as percentage of total sterols in the mud fraction [(concentration of coprostanol)/(concentration of all sterols) × 100] sampled during 1979 and concentration of the trace metal zinc [crosshatched pattern, ≥30 ppm; from (*21*)] in the bottom sediments of the New York Bight.



lations show that the rate of metal accumulation in dredge material is much greater than the rate of metal diffusion through pore water; hence it is not likely that diffusion provides significant amounts of metals to bottom waters. However, expulsion of metal-rich pore waters during compaction may constitute a significant input to bight apex bottom waters, because the volume is reduced by 47 percent during the relatively rapid transition from freshly dumped spoils to sediment deposit (*19*).

Our studies show that the dredge material dump site is subject to resuspension episodes during storms, when metal-rich pore waters may be mixed with bottom waters (*20*). Dayal *et al.* (*19*) have suggested that some of the metal is lost during the dumping process, either by desorption, by oxidation of metal sulfides during descent of the dredge material plume and subsequent formation of fine particles of hydrated metal oxides, or by outward advection of metal-rich fines in the base surge.

At first glance, the distribution of the trace metal zinc (*21*) does not appear to fit our characterizaton of the fine sediment transport system of the New York Bight apex as highly dispersive; most of the anomalous high values (>30 parts per million) fit within the Christiaensen Basin and the Hudson Shelf Valley (Fig. 4). Two separate lobes appear to mark the positions of the dredged materials and sewage sludge dump sites (Figs. 1 and 4), but these are loci of mud deposition and merely indicate that zinc is concentrated by fine sediment. Thus low zinc concentrations can be expected east and west of the Christiaensen Basin because only limited amounts of mud accumulate in these areas.

Our study (*6*) indicates that regional transport is across the shelf valley from the northeast and that, within the valley, annual mean transport is shoreward. The anomalously high zinc concentrations extending down the Hudson Shelf Valley (*21*) are interesting because they appear to contradict the results of the circulation study. An explanation for this diffusive behavior lies in the observed nature of flow characteristics in the Hudson Shelf Valley (*6*). Some flows do move down the valley, and the particles being transported are deposited there. However, sporadic shoreward flows return some (but not all) of this material.

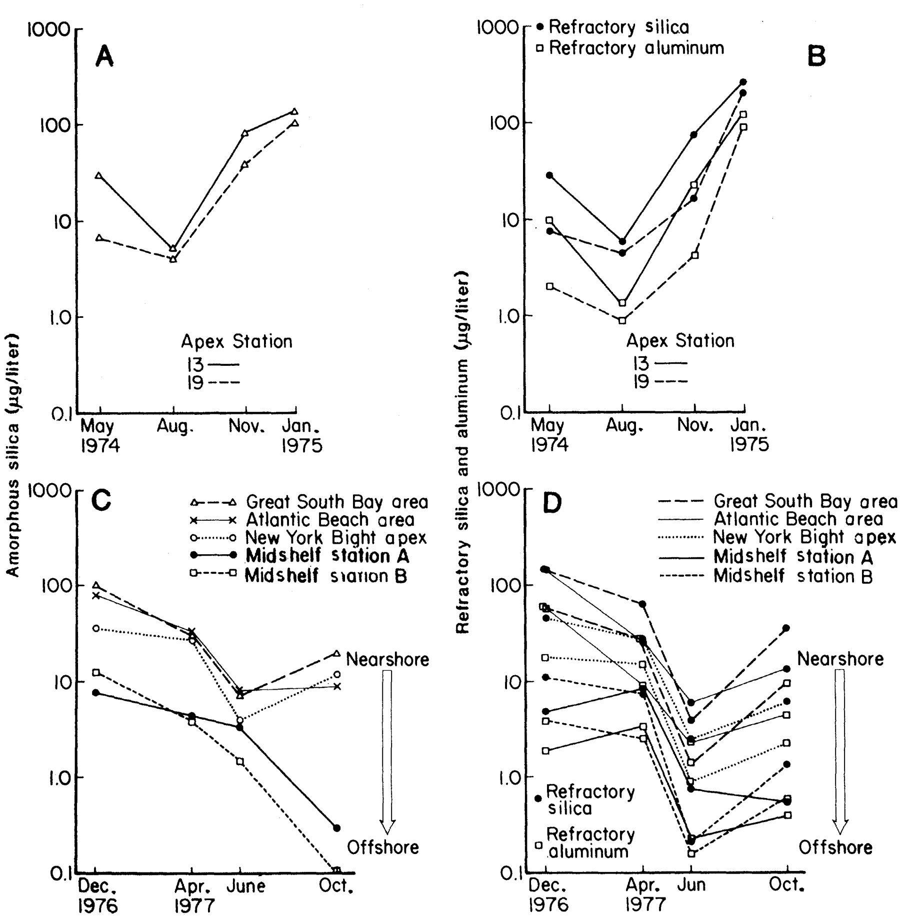


Fig. 5. Particulate-phase aluminum and silicon in the New York Bight. (A) Amorphous silica, 1974 to 1975. (B) Refractory silica and aluminum, 1974 to 1975. (C) Amorphous silica, 1977. (D) Refractory silica and aluminum, 1977.

Productivity and Particle-Associated Pollutant Dispersal

The degree to which biologic productivity affects pollutant-particle interactions is not well understood, mainly because of the complexity of organic-inorganic and organic-organic reactions. Broad seasonal changes in the composition of suspended materials are largely mediated by sediment-water interactions accompanying storms, freshwater inputs, and seasonal changes in phytoplankton populations. Our studies of the biogenic and mineral fractions of the suspended load show a relation between seasonal variations in these components and the intensity of sediment-water interactions in the New York Bight. This relation also provides some evidence that there are marked seasonal changes in particle-associated pollutant exposure to which the food web in this system is subjected.

Observations of the seasonal distribution of biologically precipitated silica (diatoms), refractory silica, and refractory aluminum for surface waters in the New York Bight are presented in Fig. 5. Since biologically precipitated silica is selectively leached before the refractory analyses (*22*), the plots for refractory silica and refractory aluminum only depict inputs from clay minerals, quartz, or feldspars (or all three). The plots include data for two stations adjacent to the southern coast of Long Island (2 km from shore), two stations in the apex (17 and 20 km from shore), and two offshore stations (55 km from shore). These diagrams reveal (i) that standing crops of both classes of suspended materials decreased from near shore to off shore; (ii) that the highest standing crops in all areas occurred in the winter and spring with the nadir in the summer and (with the exception of amorphous silica in offshore waters) then increased from summer to fall; and (iii) that refractory inorganic components and diatom-generated amorphous silica show a similar pattern of seasonal variation.

Nearshore to offshore gradients. Normally, there are large horizontal gradients in the standing crops of amorphous silica and mineralic silica and aluminum, with nearshore areas enriched more than offshore areas. This general trend has been noted for the total suspended load in the New York Bight area (*11*). Several processes probably help maintain such marked gradients from near shore to off shore; these include terrigenous inputs to nearshore areas (rivers and estuarine outputs) and sediment-water interactions, which are more likely to affect shallow, nearshore areas. The advective regime in the area also favors movement of materials along shore rather than off shore. These physical processes are probably also of first-order importance to diatoms because the same inputs that enrich the nearshore water column in refractory materials (river input and resuspension) are also accompanied by nutrient inputs that support plant growth (*23, 24*).

Seasonal variation. During the summer of 1977, high salinities and low standing crops of refractory suspended matter (Fig. 5) revealed that freshwater inputs and sediment-water interactions had little if any effect on surface waters (*25*). This seasonal pattern is consistent with that for wind stress and river discharge, both of which reach nadirs during the summer (*26*). The large temperature difference between the warm, nutrient-depleted surface waters and the cold, nutrient-rich bottom waters (*25, 27*) also restricts vertical exchange. Vertical stratification is important in constraining the effects of resuspension to areas beneath the thermocline (*11*). Suspended materials moved from surface to deeper waters are essentially lost because waters below the thermocline are effectively isolated from those above (*14*). Thus, the seasonal lows in wind stress, the terrigenous input, and the presence of a mixing barrier (thermocline) combine with biologic removal processes to produce a seasonal nadir in refractory silica and refractory aluminum in all areas.

Not surprising, for inner-shelf areas there was also a seasonal low in amorphous silica (diatoms) during the summers of 1974 and 1977 (Fig. 5). Apparently, diatom growth is limited by low nutrient concentrations whose upward fluxes are restricted by water column density gradients. The seasonal trends depicted in Fig. 5 are only for diatoms (net plankton) and do not include flagellates (nanoplankton) such as *Ceratium* species, which apparently thrive under light regimes that restrict diatom growth (*27*). This consistent seasonal cycle implies a close relation between the standing crop of biogenic silica and the extent of sediment-water interactions in the New York Bight.

Thus the physical processes controlling resuspension and sediment transport are probably also crucial to the upward movement of pore-water nutrients and thus to primary production in the New York Bight system (*24*). This may help explain the similar seasonal patterns for both inorganic and biologially produced components in the bight (Fig. 5).

An inference drawn from the above discussion is that pollutants introduced into the system, and also those within the system, might be transformed by physical, chemical, or biological processes. For example, the frequent and intense winter storms remove and reinject deposited materials (sediments and pore waters) into the upper portions of the water column. This provides an opportunity for both soluble and particulate materials to be incorporated into or deposited onto organisms or to be adborbed to and aggregated with other particulate material. Thus the likelihood for multiple transformations and extensive redistribution of both soluble and particulate phases in this ocean area is greatest during the winter months. The summer season offers a sharp contrast to the winter because sediment-water interactions are at a nadir and a density barrier essentially restricts remobilized particulate and soluble components to the lower portions of the water column. In essence, this sharply reduces the interactions between pollutants and organisms in the upper ocean as well as the distribution rates for sediment in the New York Bight.

Discussion

In geologic terms, the average 9-day residence time of a suspended particle is extremely short, and we infer that a particle released at any point must travel through many transport cycles before escaping or being deposited in a sink. Because of the many mixing and dispersion cycles and the presence of the estuarine circulation system, particles tend to diffuse shoreward, against the particle concentration gradient (*14, 15*). Our studies also indicate that particles seek certain preferred sites of deposition within the coastal zone, regardless of their point of introduction.

Although the total area in the bight presently covered by mud may be somewhat greater than when Henry Hudson's ships first visited it (*10*), there appears to be no compelling reason to believe that it is significantly different in terms of its dispersal pathways. In such highly dispersive and distributive systems, anthropogenic activities are more likely to change the composition of mud deposits than their areal distribution. We therefore infer that the distribution of muds in the New York Bight apex is controlled primarily by natural forces rather than by the activities of humans, except in the immediate area of the dredge-spoil dump site.

Because of the distributive nature of the apex system, particles tend to go to depositional sinks determined by natural transport processes, regardless of their source. These sinks are inferred to be largely within the intracoastal zone of marshes, estuaries, and lagoons, and it is these areas that may determine the pollutant-related assimilative capacity of the New York Bight apex as a whole.

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