1993

Sediment characterization of southern New England systems, the Hudson and Delaware Estuaries, Virginian Province

Maynard M. Nichols
Virginia Institute of Marine Science

Caroline Brouwer-Riel
Virginia Institute of Marine Science

et al

NATIONAL ESTUARINE INVENTORY: SUPPLEMENT

SEDIMENT CHARACTERIZATION OF SOUTHERN NEW ENGLAND SYSTEMS, THE HUDSON AND DELAWARE ESTUARIES, VIRGINIAN PROVINCE

Compiled by Project Team:

Maynard M. Nichols and Caroline Brouwer-Riel

Virginia Institute of Marine Science
School of Marine Science
College of William and Mary
Gloucester Point, Virginia 23062

and

C. John Klein III and Susan E. Holliday

National Oceanic and Atmospheric Administration
Ocean Assessments Division
Office of Oceanography and Marine Assessment
Rockville, Maryland 20852

December 1992
Revised 1993

PROJECT DESCRIPTION

NOAA's National Estuarine Inventory (NEI) is a series of related activities of the Office of Oceanography and Marine Assessment (OMA), National Oceanic and Atmospheric Administration (NOAA) that aims to develop a national estuarine data base and assessment capability. Initiated in June 1983 as part of NOAA's program of strategic assessments, the broad goal of the NEI is to build a comprehensive computerized data base for evaluating the health and status of the Nation's estuaries. It aims to bring estuaries into focus as a national resource base. Without a systematic set of data with common coordinates, units and classifications, it is difficult to analyze or compare estuaries, to assess their regional influence and to generate useful information in the form of sediment charts or desk-top computer summaries.

In May 1990 the Sediment and Contaminant Inventory (SCI) was initiated to develop a comprehensive information base on the distribution of bottom sediments and their contaminants. The SCI provides a new computer data base and it characterizes the essential and typical sedimentological features of each system. This is one step in the compilation of a regional synthesis, thus bridging the gap between site specific studies and a regional data base. The ultimate goal of the characterization is to learn the status of sediment distributions in the Nation's estuaries. It shows the most recent and mappable data that exist, where it comes from and where the gaps are that need to be filled. The data are organized into systematic data sets that are easily retrievable by personal computers. The computer will display the sediment maps together with living marine resource distributions, wetlands, pollutant sources and circulation routes to make comparisons and rankings. NOAA will ensure that the products are useful and available to coastal resource managers.

CONTENTS

EXPLANATION

Selection of Estuaries

The estuarine systems selected are from the NOAA National Estuarine Inventory in the EMAP Virginian Province (Figure 1). The principal spatial unit of each system is the estuarine drainage area (EDA) defined in the NEI data atlas (U.S. NOAA, 1985). The sediment and contaminant distributions embrace the estuarine bottom area, i.e. from the head of tides to the mouth where the estuary meets the ocean, bay or sound as determined by physiographic features (U.S. NOAA, 1985). Data coverage embraces whole estuaries and far-field distributions. Chart scales are smaller than 1:80,000 and the minimum mappable unit is 1.0 km^2 or larger except in the Hudson and Raritan Bay where 0.25 km^2 was used.

Sources of Information

Data on bottom sediment characteristics and sediment distributions come from a variety of existing sources: computer files, published and unpublished literature including masters theses, doctoral dissertations and laboratory file data. The data come in many forms: e.g. tabulations, computer tapes, graphs and charts of distributions. Data entered into the data base and used to compile charts, come from references considered primary sources whereas general information used to characterize the sediments and to interpret sedimentary processes come from references considered secondary sources.

Data Base Organization

The data were selected to provide the most up-to-date and comprehensive spatial coverage on bottom sediments. They mainly consist of laboratory processed data obtained from analysis of samples or cores collected at individual stations. For certain systems however, e.g. the Hudson, sediment information is available only as charted distributions. In this case the data base is generated by digitizing boundaries of sediment types.

The sediment "station" data are organized and processed into systematic data sets in digital form through a sequence of steps illustrated in Figure 2. (1) Once the data are identified and acquired, they are (2) inventoried and documented by bibliographic referencing, then (3) sorted by location, parameter and by spatial coverage, and (4) assessed for quality, i.e. completeness, consistency for compilation into chart "mosaics," (5) selected for inclusion in the data base with priority given to the best available, most recent and mappable laboratory processed data. Then, (6a) the point station data are reduced to common units, digitized in GIS (Geographic Information System) using either Arc Info or a Numonics NUM 2200 unit and then entered into a PC Quattro Pro spreadsheet. They are entered by data source, sample number, geographic coordinate, and parameter; textural distributions are classified into percent mud and the Shepard classification (Shepard, 1954), or mean and median particle diameter. The PC used is a NEC Powermat 3865X personal computer equipped with Map Info Map File Import/Export package. Alternately, (6b) the chart distributions are scaled to a standard NOS chart, transferred to a mylar overlay and digitized by NOAA's Arc Info unit using the GIS and a plotting package. The digitized "station" data are then (7) plotted

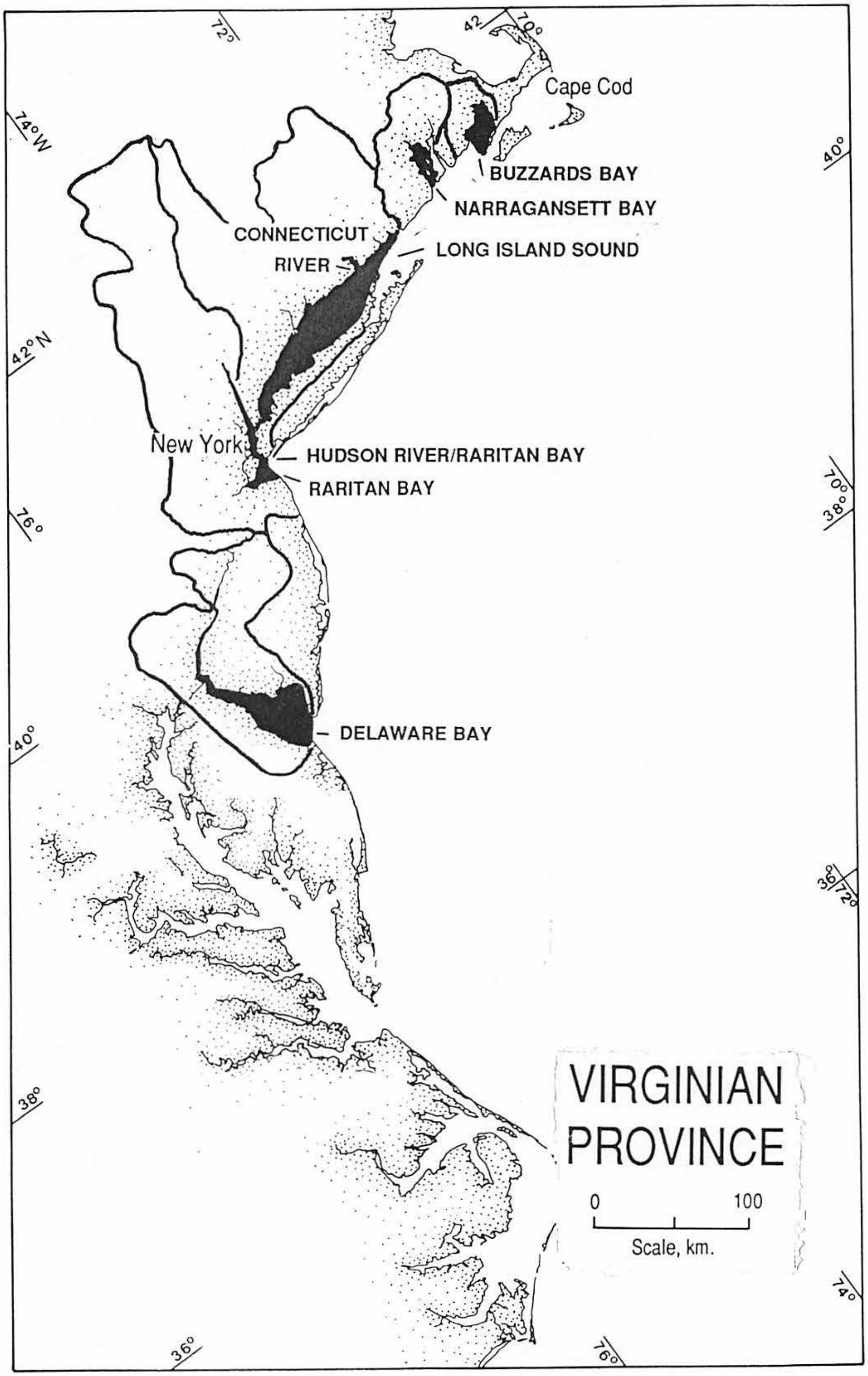


Figure 1. Location of estuarine systems characterized and included in the NEI data base from the Southern New England region, the Hudson and the Delaware Estuaries. Estuarine drainage areas, bold line.

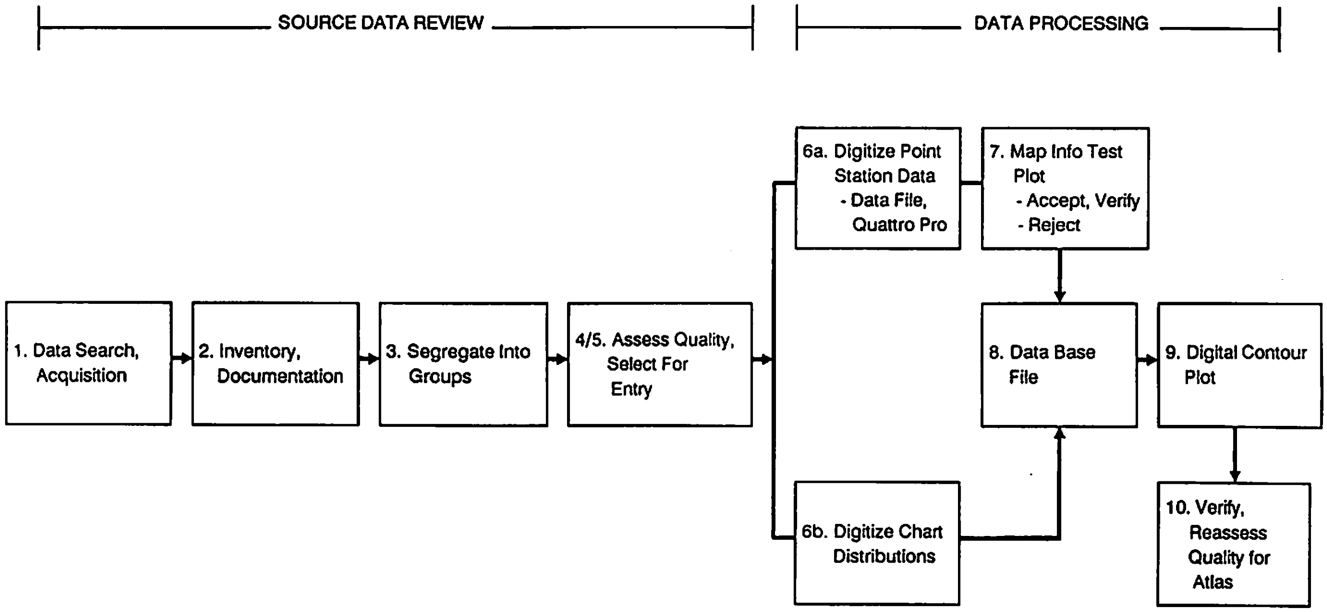


Figure 2. Scheme of organization and processing data into a computer data base and desk-top atlas.

as "test" charts that serve to validate data in the data base. The resulting distributions from steps 6b and 7 are then examined for consistency, verified and (8) stored in a computer file. (9) The file data are processed by making digital contour plots for NOAA's desk-top atlas (COMPAS) and (10) the output verified and reassessed for quality.

Data Quality

The data used are the best available and most recent mappable data for each estuary. The relative scientific certainty of the data is assessed, after initial sorting of source data and after test plotting, at two levels: (1) by data source and (2) their "mappability." Appendix 1 shows the organization of data quality, criteria used and weighting scales. The overall, or aggregate, quality is estimated by averaging the two levels of certainty after normalizing to 100 (Table 1). For example, the overall data for the Raritan Estuary is rated "highly certain." It is all laboratory processed data using standard techniques; it is largely published or semi-published data; it has a high sampling density (more than 5 - 7 stations/10 km^2) and a number of additional measured parameters, besides textural parameters, which also has a high sampling density. The data is backed by older multiple laboratory processed coverage (e.g. Kastens *et al.*, 1978).

Sediment Parameters

Sediment texture is mainly derived from laboratory mechanical analyses of sediment size. In several estuaries however, e.g. which lack laboratory processed data, sediment distributions are derived from petrographic examination (e.g. Moore, 1963). Sediment texture is mainly expressed as weight percent clay, silt, sand and gravel with textural classes following the standard Wentworth grade scale. Field sampling, laboratory processing and statistics of the size distributions often vary with investigator but no attempt has been made to modify the original data except to convert units. Readers should refer to the original data sources for procedural details. For

Table 1. Data Quality Weightings by Source and Mappability of Textural Parameters

	DATA SOURCE QUALITY								MAPPABILITY							AGGREGATE QUALITY	
NEI SYSTEM	ID	S1	S2	S3	S4	SS	ST	SQ	M1	M2	M3	M4	MS	MT	MQ	AQ	DATA QUALITY
Buzzards Bay	1	3	1	3	2	1	10										
	AVERAGE							67	1	1	3	1	1	7	58	63	FAIRLY CERTAIN
Narragansett Bay	1	3	3	2	4	0	12	80									
	2	3	3	2	1	0	9	60									
	3	3	3	2	4	0	12	80									
	AVERAGE							73	3	3	2	1	0	9	75	74	MODERATELY CERTAIN
Long Island Sound	1	3	2	2	1	1	9										
	AVERAGE							60	1	3	3	1	1	9	75	68	FAIRLY CERTAIN
Connecticut River	1	2	1	3	3	0	9	60									
	AVERAGE							60	2	1	3	1	1	7	58	59	FAIRLY CERTAIN
Hudson R./Raritan Bay	1	3	3	2	2	1	11	73									
	2	3	1	2	2	1	9	60									
	3	3	1	2	1	0	7	47									
	4	3	1	1	2	0	6	40									
	5	3	2	3	5	1	14	93									
	AVERAGE							63	3	3	1	1	1	9	75	69	FAIRLY CERTAIN
Raritan Estuary	1	3	2	2	5	1	13	86									
	2	3	1	1	5	0	10	67									
	3	3	1	3	4	1	12	80									
	AVERAGE							78	3	3	3	2	1	12	100	89	HIGHLY CERTAIN
Delaware Bay	1	3	3	2	2	0	10	67									
	2	3	1	2	1	0	7	46									
	AVERAGE							57	1	3	3	1	0	8	66	61	FAIRLY CERTAIN

KEY:

DATA SOURCE QUALITY

- ID: SOURCE ID*
- S1: DATA FORMS
- S2: DEGREE OF LAB PROCESSING
- S3: DOCUMENTATION
- S4: SAMPLING DENSITY
- SS: ADDITIONAL PARAMETERS
- ST: SUM OF THE WEIGHTINGS
- SQ: NORMALIZED WEIGHTING

* Number corresponds to reference in characterization summary for each system

MAPPABILITY

- M1: SAMPLING DENSITY
- M2: SPATIAL COVERAGE
- M3: CONSISTENCY
- M4: TEMPORAL COVERAGE
- MS: ADDITIONAL PARAMETERS
- MT: SUM OF THE WEIGHTINGS
- MQ: NORMALIZED WEIGHTING

AGGREGATE QUALITY

AQ (SCALE)	DATA QUALITY
Over 85	HIGHLY CERTAIN
70 - 85	MODERATELY CERTAIN
55 - 70	FAIRLY CERTAIN
40 - 55	REASONABLE INFERENCE
Below 40	DOUBTFUL

estuaries lacking data expressed as clay, silt and sand percent, the percentage of sand, or clay, and of "mud" (i.e. silt plus clay) is used. Alternately, data for the statistical parameters mean, median or modal diameters are used. Where textural data from several reliable data sources are available, the most compatible data are used to compile a chart "mosaic."

Organic matter reflects the incomplete oxidation of organic tissues of plants and animals stored in the sediments. Organic matter produced in an estuary includes plankton, grass, plant detritus and fecal material whereas organic matter supplied from external sources as banks and streams includes tree leaves, wood fragments and sewage. Total carbon (carbonate plus organic carbon) is usually measured by high temperature combustion in an induction furnace. Organic carbon may also be measured by high combustion after removal of carbonate by acid digestion). Organic matter is usually found by weight loss after oxidation such as treatment with hydrogen peroxide or loss on ignition. Since organic carbon represents about half of the total organic matter, organic matter percentages are also derived by multiplying organic carbon values of the original data by a factor of 1.8 following Bader (1954, 1955). Sediment organic carbon and/or organic matter are linearly related to the nitrogen content with ratios of about 11 to 13 (Bader, 1955). These parameters therefore, are an indication of eutrophic substances.

Water content of the sediments represents the weight percentage of water in a given sediment mass to the wet weight of sediment. It is usually determined by weight loss after drying. Water content is inversely proportional to grain size and bulk density, and directly proportional to porosity (Bennett and Lambert, 1971).

Short-term rates of sedimentation spanning decades (< 150 years B.P.) are determined from either bathymetric changes or geochronology. Bathymetric changes are measurements of shoaling or deepening of the bottom between successive depth surveys (Shepard, 1953). These changes reveal spatial patterns of sedimentation rate but are usually not as precise as radiometric measurements of sediment age with depth in sediment cores, e.g. ^{210}Pb and ^{137}Cs. The ^{210}Pb measurements reveal temporal variations with depth and are sensitive to local variations. Another method utilizes the abundance of pollen grains (Brush, 1986) in cores relative to average rates of sedimentation within a radiocarbon-dated depth interval. Where most sediment accumulates in dredged channels, maintenance dredging records of depth changes also provide useful data.

Mass Balance and Storage Efficiency

The status of sediment sources and losses is given by:

$$\underset{\text{(sources)}}{Mi} = \underset{\text{(losses or removal)}}{Ms + Me}$$

Assuming steady state over the long-term then the input flux, Mi, must equal the output flux, Me, and the flux to the bed, Ms. Biogenic production (P) and consumption (C) are neglected since they are usually small. The sources and losses of sediment vary with investigator, and with methodology or data uncertainties. Thus, a range of estimates is presented. The storage efficiency, Si, is the ability of an estuary to retain and accumulate sediment delivered to it (Nichols, 1986). This is expressed as a ratio of the mass rate of accumulation to the rate of input over a given time. Thus:

$$Si = Ms/Mi$$

The storage efficiency ratio is referred to the fluvial input mass which is usually known. Therefore, a ratio of one implies the amount of sediment accumulated is equivalent to the amount supplied by the river(s). A ratio greater than one implies an estuary stores more sediment than supplied by its rivers whereas a ratio less than one implies the estuary stores an amount less than the total fluvial input, a situation when fluvial sediment is transported through an estuary.

Pollution Susceptibility

The relative status of pollution is partly characterized by their susceptibility to pollution, i.e. the potential for pollution as determined by hydraulic characteristics and by the exposure to anthropogenic activities in the watershed. Following Biggs *et al.* (1989) the susceptibility characteristics are:

1. <u>Hydraulic Character - HL</u>

   Hydraulic loading which is the contaminant handling capacity of a system based on the volume and flushing. It includes both freshwater and tidal flushing and indicates how well an estuary can dilute or transport contaminants. When hydraulic loading is low flushing is sluggish and the estuary tends to retain contaminants.

2. <u>Stratification - STRAT</u>

   Estuaries with strong vertical salinity gradients are likely to develop hypoxia or anoxia and to recycle nutrients more efficiently than homogeneous systems.

3. <u>Population/Estuary Surface Area - P/EA</u>

   This ratio expresses the estuary loads of anthropogenic substances likely to result from watershed activity particularly point sources. When P/EA is high, nutrient loads to the estuary may be high.

4. <u>Agriculture Workers/Estuary Surface Area - AG/EA</u>

   This ratio expresses the estuary loads of anthropogenic substances likely to result from watershed activity particularly non-point sources. When AG/EA is high, nutrient and toxic loads to the estuary may be high.

5. <u>Chemical Workers + Population and Estuary Area - C + P EA</u>

   This relation expresses the estuary loads of anthropogenic substances likely to result from watershed activity, particularly point sources. When these values are high, toxic loads to the estuary may be high.

The parameters "3," "4," and "5" are ratios of the anthropogenic watershed activity to the hydraulic loading, parameter "1". They express the concentrations of pollutants that could result considering the given load to the system and the systems ability to flush that load to sea. The relative ranking, high, medium and low, in the characterization summaries is based on comparison of 78 U.S. estuaries from the National Estuarine Inventory (Biggs *et al.*, 1989).

SEDIMENT CHARACTERIZATION

M010 BUZZARDS BAY

Buzzards Bay is a large deep embayment at the western boundary of Cape Cod. It lies behind the Elizabeth Island chain that provides partial protection from open ocean swell. Configuration and bathymetry are shaped by glacial action. The southeastern shore, i.e. the Elizabeth Islands, consists of a frontal moraine while the northwestern shore, which lies normal to the moraine, consists of a series of headlands and intervening drowned valleys and elongate glacier scoured troughs that follow former fluvial valleys. The pattern is reflected at depth by a dendritic pattern in the 10 m depth curve (Moore, 1963). The bathymetry is modified by dredged channels cut about 10 m deep leading to New Bedford and to the Cape Cod Canal. Dredged material dump sites lie south of West Island and west of West Falmouth.

Sediment sources are poorly known but fluvial input of fine sediment is likely very low because of resistant terrain in the watershed with little erodable soil and poor drainage. In contrast, much silt probably comes from marine areas as well as erosion of shore bluffs typically composed of glacial till. Glaciers were responsible for eroding granodiorite north and west of the bay and delivering large amounts of till and outwash sediment to the coast (Fitzgerald *et al.*, 1987). In a regime of rising sea level these deposits have been reworked by storms, waves and tidal processes. This has led to formation of barrier beaches, spits and beach ridge barriers in front of many Holocene drowned valleys on the northwest shore (Fitzgerald *et al.*, 1987). Additionally, reworking of relic glacial deposits on the bay floor by storm waves likely supplies some fine material while benthic production on the bay floor supplies shell.

Fine sediment is likely transported into the bay mainly from marine areas by tidal currents but the pathways and mechanisms are not well known. Near-surface tidal currents are relatively strong near the entrance (~ 0.7 m/s) and in passages through the Elizabeth Islands (0.9 to 1.2 m/s) but weak in central reaches (< 0.25 m/s) (Moore, 1963). Consequently, the central floor is a major sink and accumulation has produced a gently sloping floor. Additionally, benthic organisms encourage deposition by pelletizing filtered sediment (Sanders, 1958). Prior to deposition, the top 2 to 3 cm of fine sediment is resuspended many times by tidal currents and storm waves. Most fluvial fine sediment is likely retained in the northwest harbors and tributaries together with marine material added by landward flow of the estuarine circulation (Summerhayes *et al.*, 1985). Small amounts however, escape to the open bay basin.

Bottom sediments are fine-grained, i.e. coarse silt, in deeper parts greater than 10 m, and display a pattern reflecting the relic drainage troughs (Figure 2A and 2B). In contrast, they are coarse-grained, i.e. very coarse to coarse sand or gravel, in shallow, wave exposed zones, less than 6 m, either nearshore or on topographic highs. However, gravel occurs in deep zones of fast currents near the entrance and in passes through the Elizabeth Islands. Fine sediment also resides in nearshore tributaries, harbors and embayments where energy is low (Summerhayes *et al.*, 1985; Frey *et al.*, 1989). Organic matter in the fine-grained sediments, which are colored black, average about

3.8%. In New Bedford Harbor where sewage outfalls and ships discharge wastes, concentrations reach 17.3% (Summerhayes *et al.*, 1985). Much of the organic material on the bay floor consists of fecal pellets of deposit feeding pelycypods (Rhoads, 1967).

The main depocenter of mud sedimentation lies in deep central basins where rates of sedimentation are 1.0 to 2.95 mm/yr (Summerhayes *et al.*, 1985). These rates are about the same as the short-term rates of submergence, i.e. 1.8 to 2.8 mm/yr (Emery and Aubrey, 1991). Locally rates reach 15 to 40 mm in harbors such as New Bedford (Summerhayes *et al.*, 1985). Fast rates are induced by dredging and by enclosure of the harbor entrance with a hurricane barrier.

Buzzards Bay receives contaminants from wastewater treatment plants and industrial discharges mainly at, or near New Bedford (Summerhayes *et al.*, 1985). Sediment contamination by metals is marked, i.e. Cu, Cr, Pb and Zn, and extends to the central bay where concentrations are about 5% those at New Bedford. Additionally, the central bay is contaminated with PCBs and hydrocarbons; some are probably derived from atmospheric fallout. Pollution susceptibility for toxics is high because of low flushing ability and a locally high population in the drainage area relative to bay area (Biggs *et al.*, 1989).

Bottom Sediment Charts

The bottom sediments throughout the main portion of Buzzards Bay were sampled at 150 stations by J. Robert Moore in 1953, 1954, and 1955 (Moore, 1963). Core stations were positioned by ranging and sextant angles on landmarks.

The distribution of clay percentage, Figure 2A, is not necessarily a textural pattern but a compositional pattern based on thin-section microscopy. In deep zones however, the pattern follows the textural pattern of median diameter (silt) based on mechanical sieving analyses and Wentworth size classes, Figure 2B. The chart was compiled by computer mapping Moore's numeric data using a minimum mappable unit of one square kilometer. The major sand and clay boundaries are essentially the same as those charted by Hough (1940) from samples collected 20 years earlier in 1934.

For sources of information and explanation of data in the sediment inventory summary, see text and Appendix 2.

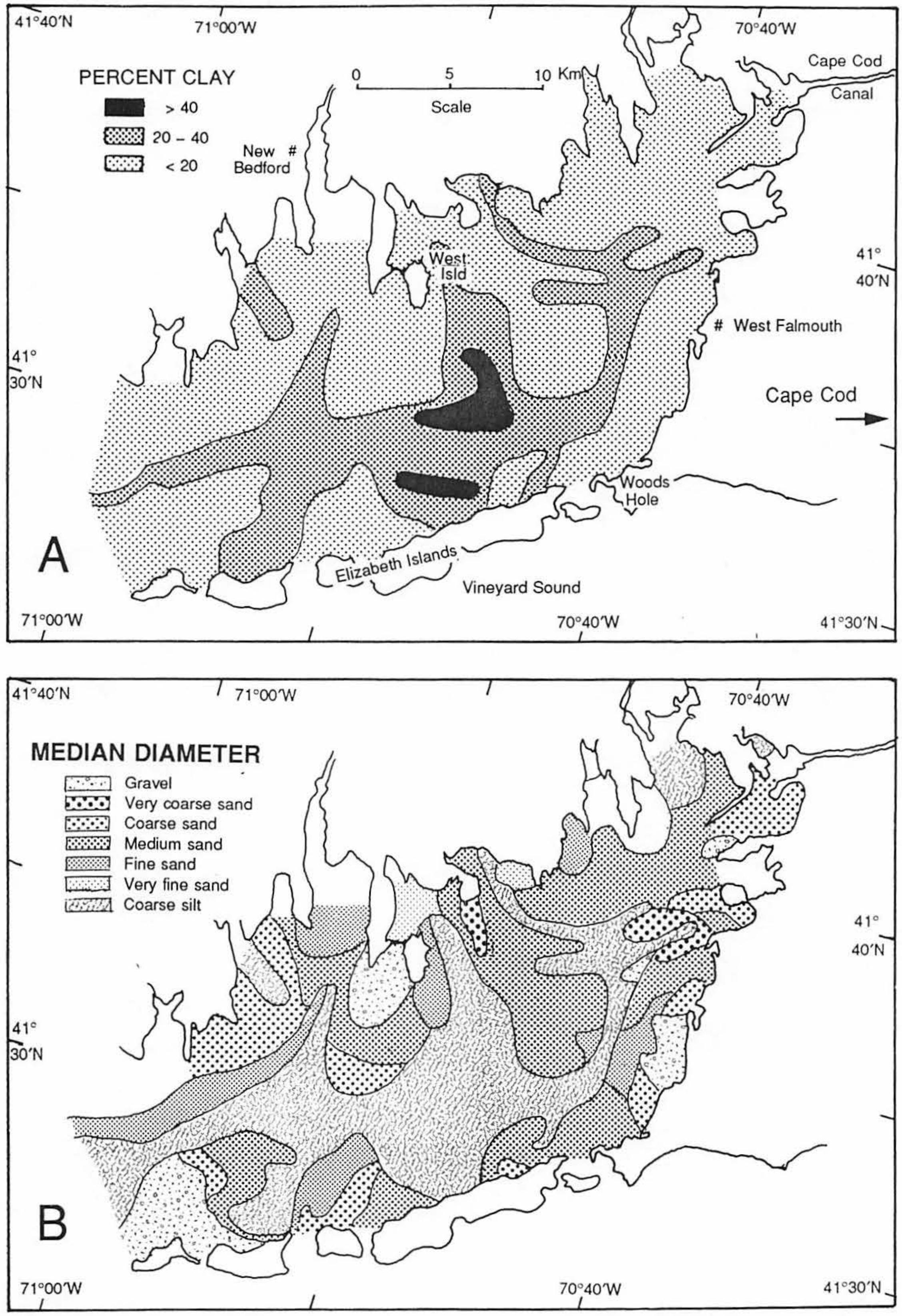


Figure 2. A. Distribution of percent clay in Buzzards Bay.
B. Distribution of sediment texture in terms of median grain diameter following Wentworth size classes.

SEDIMENT INVENTORY

M 010 BUZZARDS BAY

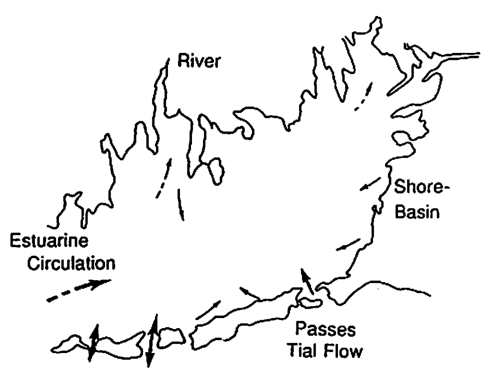
Drainage and Morphology

Total Drainage Area, Km^2	1,554
Average River Inflow, m^3/s	34
Length, Km	45
Average Depth, m	11
Average Width, Km	13
Width/Depth Ratio	1182
Surface Area, Km^2	590

Sources

	Relative Strength*
Drainage Basin	Very low
Shores	Low
Marine	Moderate
Production	Low
Sewage	Low

Pathways



Submergence Rates

Short-term mm/yr	1.8-2.8
Long-term, mm/yr (0-4,000 yrs BP.)	2.5 (?)

Sinks

	Relative* Strength
Central Floor	Moderate
Tributaries, Harbors	Low-moderate

Sedimentation Rate, mm/yr	
Central Basin	1.0-2.95
Harbors	15-40

*For total sediment

Bottom Sediment

Clay Area (>30%), %	19
Sand Area (>60%), %	81
Organic Matter, Av. %	3.8

Dominant Pattern:
Clay and silt in basins and northern tributaries; sand on shoals; gravel at entrance

Pollution Susceptibility

High due to low flushing ability and locally high anthropogenic population in the drainage basin.

Data Quality, Bottom Sediment Texture

Fairly Certain

SEDIMENT CHARACTERIZATION

M020 NARRAGANSETT BAY

Narragansett Bay is shaped into three main interconnected passages, small bays, reentrants and intervening islands which trend north-south. This trend reflects a southward flowing drainage pattern incised in pre Holocene bedrock erosional valleys which were later modified by glacial erosion and deposition (McMaster, 1984). The present-day Bay began to form about 9,000 years ago as sea level rose, drowned and infilled the valleys with a variety of sediments. Dredged channels cut 10 - 12 m into the Providence River and 10 - 11 m into Mount Hope Bay - Fall River area. Much material is disposed in a deep hole southeast of Prudence Island, as well as off Conanicut Island, around Spar Island in Mount Hope Bay while some is dumped offshore in Rhode Island Sound (Santschi *et al.*, 1984; Seavey and Pratt, 1979).

Most of the freshwater input is low, 100 m^3/s, and dammed. Freshwater flows almost directly into saline reaches about 25 $^o/oo$ salinity without passing through a long mixing zone (Nixon, 1985). Thus, a turbidity maximum is lacking, the mid and lower bay is well-mixed vertically and fluvial sediment input is very low, about 0.1 x 10^6 m tons/yr (assuming the erosion rate is the same as for Long Island Sound). Fine sediment is also derived from marine areas via the landward estuarine flow. Some material is derived by storm wave erosion of glacial deposits along the shore or by reworking of older Bay floor deposits (Morton, 1967).

Within the Bay, fine sediments are redistributed by tidal currents and the estuarine circulation with superimposed wind forcing. The estuarine circulation is pronounced in the Providence River where waters are partially mixed and the dredged channel focuses landward flow (Spaulding, 1985). East Passage is the main avenue of transport being two times greater than West Passage. Wind forcing on the offshore shelf causes landward flow through West and Sakonnet Passages and return flow through East Passage (Spaulding, 1985). For offshore winds the transport direction is reversed. Additionally, nearshore sand is likely transported into the Bay via littoral currents around entrance headlands at Point Judith and Sakonnet Point (Morton, 1967).

The main sinks of mud accumulation are in channels of near-river areas, e.g. Providence River, and upper Narragansett and Mount Hope Bays (Santschi *et al.*, 1984). Additionally, mid-Bay zones southwest and northeast of Prudence Island having long tidal slack currents are significant. Accumulation ranges 1.0 to 5.0 mm/yr being faster in the upper Bay than the lower Bay (Corbin, 1989). Rates are likely much higher in dredged channels. Accumulation rates average 3.0 mm/yr for the entire Bay (Santschi *et al.*, 1984) while sea level rise is 1.5 to 2.6 mm/yr (Emery and Aubrey, 1991). Total accumulation of fluvial fine sediment amounts to about 0.07 to 0.09 x 10^6 m tons or 70 to 90% of the input (Santschi *et al.*, 1984). Accumulation in dredged channels is 5 to 7 times greater than non-dredged areas. The Bay likely traps additional amounts of fine sediment from marine and shore sources.

Mud (> 80%), is abundant in channels of near-river areas but also occurs in a large zone southwest of Prudence Island. Mud is also abundant in lateral reentrants as Greenwich Bay and in deeper parts of Sakonnet Passage (McMaster, 1960). These zones are bordered by zones of coarser sediment that form a transition of mixed sediment between mud and sand. Gravel patches occur locally as unburied lag of older glacial deposits. In general, texture coarsens seaward from the mid-Bay to the entrance where currents and waves are stronger (McMaster, 1960).

Upper Narragansett Bay is heavily loaded in nutrients and metals (Nixon, 1985; Nixon *et al.*, 1986). Sewage treatment plants on the Providence River are the major source of anthropogenic metals. Additionally, sewage enters from the Fall River, Seekonk River, West and East Passages and Greenwich Bay. Besides metals, urban runoff and industrial discharges supply petroleum hydrocarbons and PAH's. Metal concentrations generally diminish exponentially seaward from the Providence River mainly as a result of freshwater dilution (Corbin, 1989; King, 1992). Pollution susceptibility to toxics in the upper Bay is high with respect to flushing ability (Biggs *et al.*, 1989).

Bottom Sediment Charts

The bottom sediments of Narragansett Bay have been thoroughly surveyed in 1956 by McMaster (1956); McMaster and Clarke (1956); McMaster *et al.* (1956); McMaster (1960) from 942 grab samples at intervals of one-half minute in latitude and longitude.

The distribution of mud abundance (Figure 3A) is classified into three groups and mapped by computer. This classification displays major patterns for recognizing dominant features. The chartlet, together with textural patterns (Figure 3B), was compiled using a minimum mappable unit of 1 km^2 and smoothing isolines. Because of the small page size scale, narrow transition zones of texture, such as occur between shoals and channels, are not represented. Greater detail can be acquired by mapping the original data at larger scales and small class intervals.

For sources of information and explanation of data in the sediment inventory summary, see text and Appendix 2.

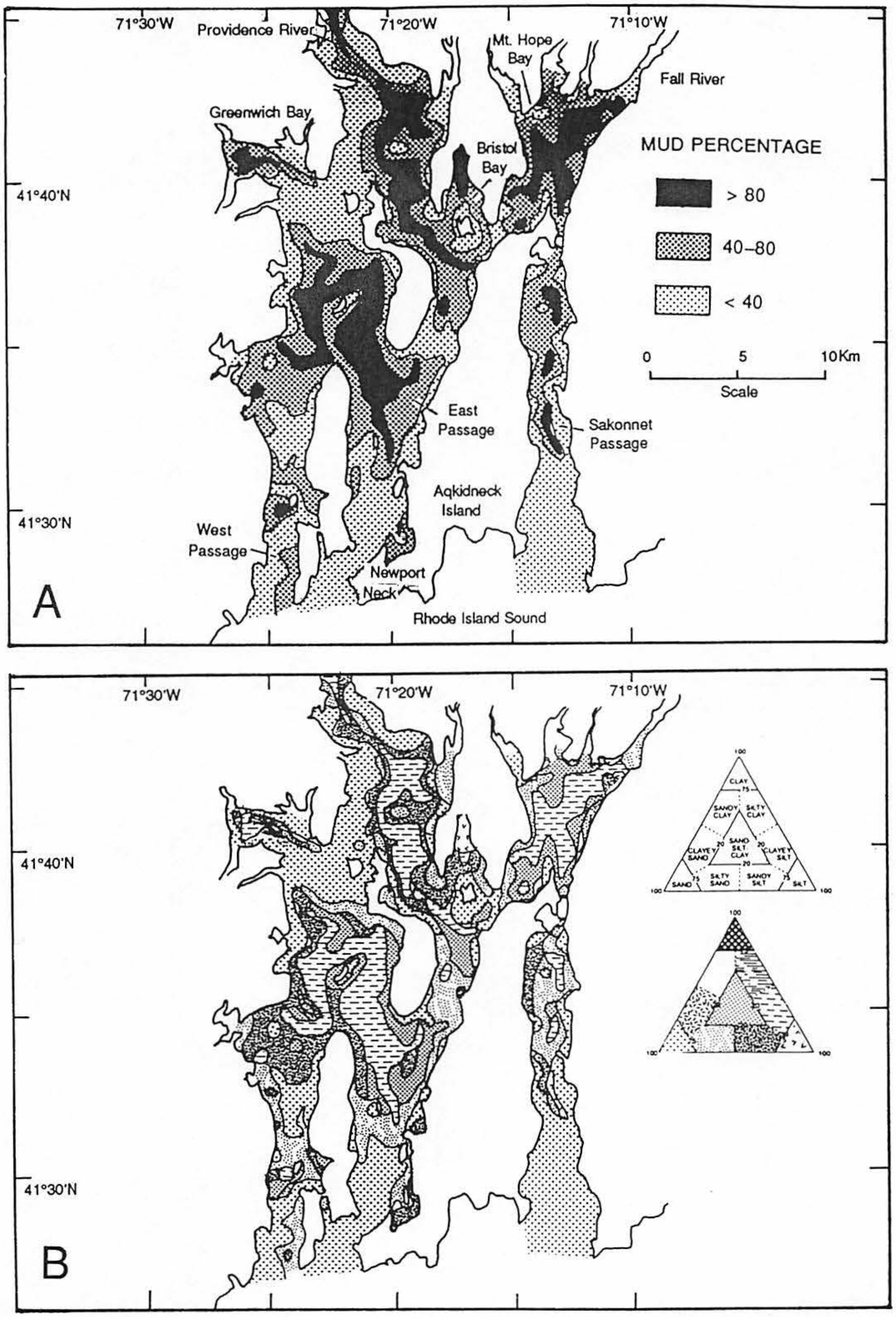


Figure 3. A. Distribution of percent mud in Narragansett Bay.
B. Distribution of sediment texture following the Shepard classification.

SEDIMENT INVENTORY

M 020 NARRAGANSETT BAY

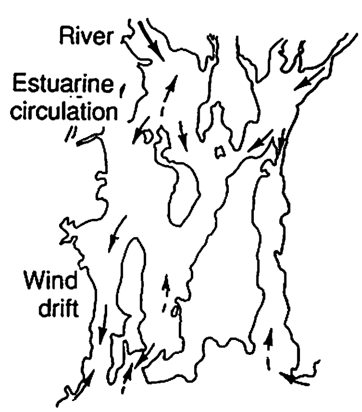
Drainage and Morphology

Total Drainage Area, Km^2	4,660
Average River Inflow, m^3/s	90
Length, Km	64
Average Depth, m	9.5
Average Width, Km	8.5
Width/Depth Ratio	8947
Surface Area, Km^2	427

Sources

	Relative Strength*
Drainage Basin	Very low
Shores	Low
Marine	Moderate
Sewage	Low

Pathways



Submergence Rates

Short-term mm/yr	1.5-2.6
Long-term, mm/yr (0-4,000 yrs BP.)	2.5 (?)

Sinks

	Relative* Strength
Upper Bay Channels	Moderate
Lower Bay Passages	Low

Sedimentation Rate, mm/yr	
Average, Bay-wide	3.0
Upper Channels	17.0
Lower Passages	1.3

*For total sediment

Bottom Sediment

Mud Area (>40%), %	50
Sand Area (>60%), %	50
Water Content, Av. %	48
Organic Matter, Av. %	2.2-4.6

Dominant Pattern:
Mud in channels near-river and upper upper embayments.
Sand in passages and near entrance.

Pollution Susceptibility

High in upper Bay due to low flushing ability and anthropogenic activity.

Data Quality, Bottom Sediment Texture

Moderately Certain

M040 LONG ISLAND SOUND

Long Island Sound is a large, 200 km-long estuary that is highly impacted by massive urbanization. More than eight million people reside in the drainage basin and along shores. It is used for shipping, waste disposal, recreational boating and it supports large recreational fisheries (Koppleman *et al.*, 1976; Greig and McGrath, 1977).

The Sound is shaped into a long trough with a deep central basin divided into three sub-basins (Schubel, 1987). It is bounded by sills at the east and west ends. The trough was carved by ancient fluvial erosion and later filled with glacial deposits of sand, gravel and boulder fill as the ice sheet melted. When the ice sheet retreated to the Connecticut shore, melt waters formed a large lake floored by mud deposits in the central basin. The present-day Sound began to form 8,000 years ago as sea level rose and drowned the trough (Gordon, 1980). The Sound exchanges water with the ocean through two connections: 1) to the east through Block Island Sound; and 2) to the west through New York Harbor. The west entrance is the most important source of freshwater that drives the estuarine circulation (Wilson, 1987). Dredged channels cut into 25 harbors around the Sound and the bulk of this material (~ 97 x 10^6 m^3) is dumped at open-water sites within the Sound (Bokuniewicz *et al.*, 1979).

There is no large fluvial sediment input into the Sound. It is estimated that about 40% of the total fine sediment input is supplied from the drainage basin via rivers, mainly the Connecticut River (Kim and Bokuniewicz, 1991). Additionally, about 14% comes from urban runoff and sewage in the drainage basin (Farrow *et al.*, 1986). An estimated 2% of the fine sediment comes from wave-cut bluffs of Long Island (Tanski, 1981). The largest supply, an estimated 45%, is derived from marine areas but a portion may include material recycled from the Connecticut River.

Once in the Sound, fine sediments are redistributed by tidal currents and the estuarine circulation. Marine material is carried westward in the lower layer (Bokuniewicz and Gordon, 1980). Prior to permanent deposition, a large amount of sediment is resuspended and redeposited, e.g., an estimated seven million tons daily (Kim and Bokuniewicz, 1991). The bulk of the total input therefore, is maintained in suspension before it is deposited.

The main sink of mud sedimentation is in two basins of the central and western Sound, i.e. west off the Housatonic River. Accumulation averages about 0.7 to 0.9 mm/yr (Kim and Bokuniewicz, 1991). This contrasts to 10 to 76 mm/yr or an average of 39 mm/yr in the dredged harbors of Connecticut (Bokuniewicz *et al.*, 1979). The main sink of sand is on the eastern Sound floor (Bokuniewicz, 1980).

Sea level rise, i.e. 3 mm/yr (Emery and Aubrey, 1991), exceeds the sedimentation rate and suggests the Sound is an effective trap for fine sediment. Since the total deposition is estimated at 1.6 x 10^6 m tons/yr, then the storage efficiency is about 2.4 to 3.1. This means the Sound not only traps an amount equivalent to its river input but large amounts from other sources probably marine areas.

Mud (> 80%), mainly silt, covers the basin floor of the central and western Sound below the 10 m depth where tidal currents and wave action are relatively weak (Reid *et al.*, 1979) (Figure 4A). In contrast, sand (> 60%) covers the eastern one-third of the Sound besides sills between the basins. The sand coarsens eastward toward the entrance where strong tidal currents and ocean waves scour and rework glacial outwash sand (Bokuniewicz, 1980). They form giant sand waves and remove fine sediment that is likely transported westward in the lower layer. Sand also extends nearshore along central Long Island close to its source in bluffs (Figure 4B). Fine sediment is likely winnowed out and deposited in less energetic deep basins. Between mud and sand zones, at intermediate depths, there is a transition of mixed sediments (40 - 80% mud) representing a net flux of sand over accreting mud deposits (Bokuniewicz, 1980). Organic matter is less than 1% in the sandy sediments of the eastern portion and 9 to 10% in muddy deepwater basins (Reid *et al.*, 1979).

Pollution susceptibility is high because of low flushing ability and the high population relative to estuary area (Biggs *et al.*, 1989).

Bottom Sediment Charts

The bottom sediments throughout Long Island Sound were sampled by Reid *et al.* (1979) from 0.1 m^2 bottom grabs at 141 stations located on 3 to 5 km north-south transects and spaced 8.7 km apart. Stations were positioned by loran A or C, fathometer and augmented by sextant bearings and ranges on landmarks or buoys when possible. Grain size analyses were performed by wet sieving and pipette.

The distribution of mud abundance (Figure 4A) is classified into three groups and mapped by computer. This classification displays major patterns for recognizing dominant features. The chartlet, together with textural types classified by the Shepard triangle (Shepard, 1954) (Figure 4B) was compiled using a minimum mappable unit of 4 km^2 and smoothing isolines. Narrow transition zones and small isolated patches are not shown. Greater detail can be obtained by mapping the original data at larger scales and smaller class intervals.

For an explanation of data in the sediment inventory summary, see text and Appendix 2.

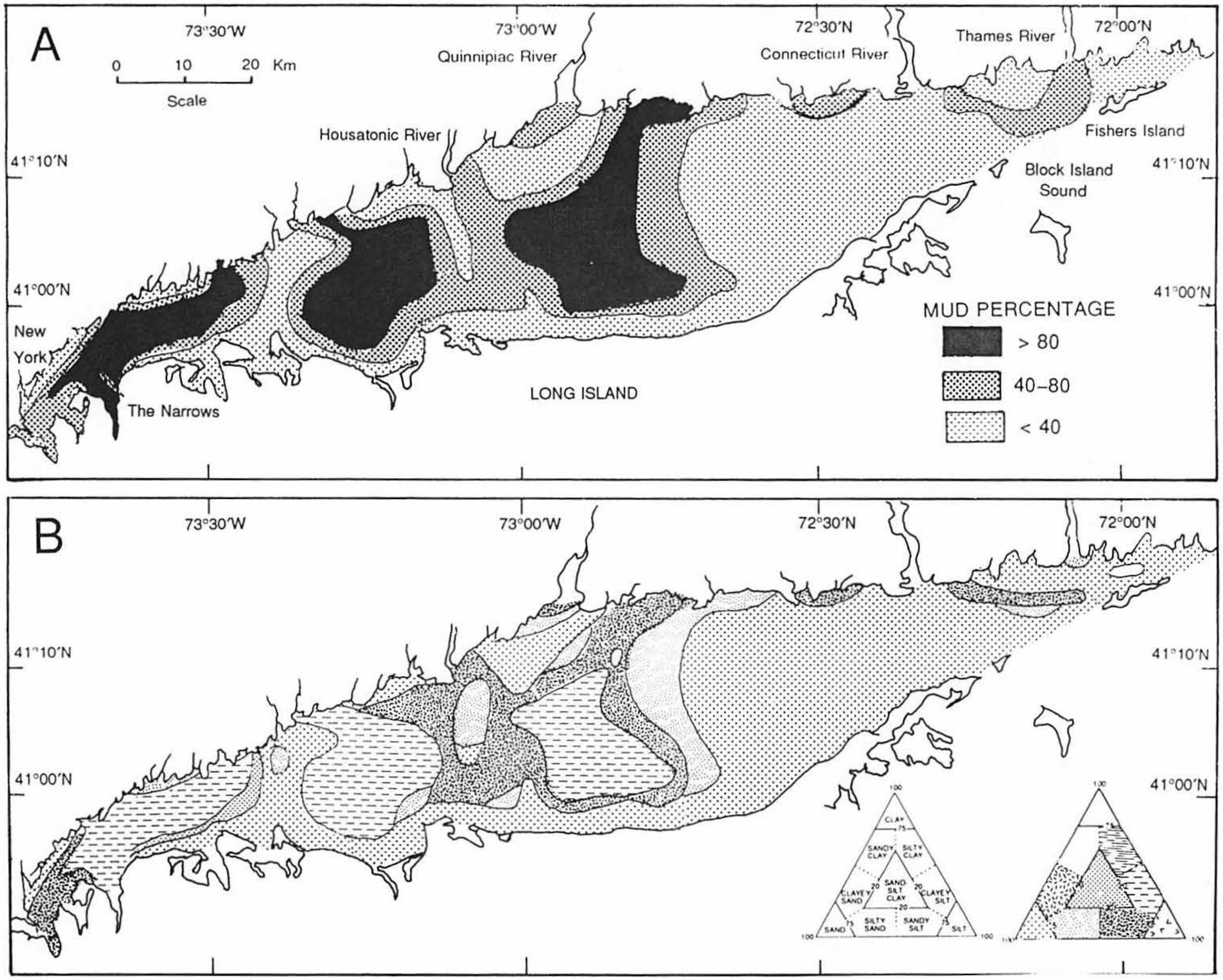


Figure 4. A. Distribution of percent mud in Long Island Sound.
B. Distribution of sediment texture following the Shepard classification.

SEDIMENT INVENTORY

M 040 LONG ISLAND SOUND

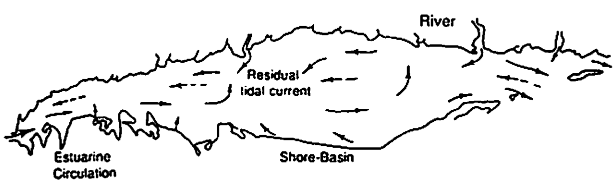
Drainage and Morphology

Total Drainage Area, Km^2	44,550
Average River Inflow, m^3/s	850
Length, Km	204
Average Depth, m	19
Average Width, Km	28
Width/Depth Ratio	1474
Surface Area, Km^2	3,320
Sinuosity	1.0

Sources

	Tons/yr x 10^6	Relative Strength%*
Drainage Basin	0.36	40
Shores	0.02	2
Marine	0.41	45
Urban Runoff	0.12	13
TOTAL	0.91	

Pathways



Submergence Rates

Short-term mm/yr	1.5-2.6
Long-term, mm/yr (0-4,000 yrs BP.)	2.5 (?)

Data Quality, Bottom Sediment Texture

Fairly Certain

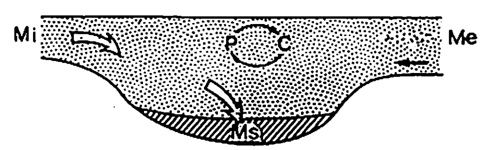
Sinks

	Tons/yr x 10^6	Relative * Strength
Basins	1.3	81
Dredged Harbor & Channel	0.3	19
TOTAL	1.6	

Sedimentation Rate, mm/yr	
Average	0.1-0.9
Basins	<0.5; 0.9
Dredged Harbors	10-76

*For fine sediment

Mass Balance



$$Mi + P = Ms + C + Me$$

(Sources) (Losses)

$$0.9 = 1.6 - 0.07 \times 10^6 \text{ tons/yr}$$

$$\text{Storage Efficiency: } Si = \frac{Ms}{\Sigma Mi} = 2.6 \text{ to } 3.3$$

Bottom Sediment

Mud Area (>40%), %	49
Sand Area (>60%), %	51
Organic Matter, Av. %	1.0
Range, %	1-9

Dominant Pattern:

Mud basins, western portion.

Sand, sills, eastern floor and near Long Island shore.

Pollution Susceptibility

High due to low flushing ability and high population relative to estuary area.

SEDIMENT CHARACTERIZATION

M040a CONNECTICUT RIVER

The Connecticut River is New England's largest and longest drainage basin covering 29,000 km^2. It contributes 71% of the total freshwater input, and much of the suspended sediment load, to Long Island Sound (Kim and Bokuniewicz, 1991). Contaminant loading however, is limited because of low metal activity in the basin and low sewage input (Farrow *et al.*, 1986). Much waste is transported to Long Island via barge.

The Connecticut River estuary is a small river mouth estuary dominated by sand. Although the tide extends over 100 km landward the normal salinity limit extends only 15 km landward (Horne and Patton, 1989). This zone consists of a low relief coastal plain. The seaward portion of the estuary extending 5 km south of the Amtrak bridge, is funnel-shaped with an axial channel flanked by shoals. This bathymetry and the lateral reentrants, originated by drowning glaciated fluvial topography (Horne and Patton, 1989). Bathymetric changes are small, except where dredged channels cut across shoals in the main channel to 3.3 to 4.0 m depths. Maintenance dredging however, is limited except in the jettied entrance channel (Scatena, 1982). Changes also occur east of the jetties off Lynde Point where a broad shoal built up 1.5 m between 1925 and 1979. Overall sedimentation and sediment storage is relatively low in the estuary because the bathymetry is in near-equilibrium with the river sediment supply (Horne and Patton, 1989).

The drainage basin is the dominant sediment source supplying the bulk of the load during short periods of river flooding (Horne and Patton, 1989). Most river-borne suspended load is derived from river bank erosion, or from material temporarily stored on the bed during normal river inflow. Small amounts of fine sediment are carried into the lower estuary via the lower estuarine layer during normal or low river inflow, a time when the estuary is partially-mixed. Although most of the suspended load is discharged into Long Island Sound during river floods, when the estuary is completely river-dominated, some fines are retained in coves, marginal reentrants, e.g. South Cove, North Cove, and marshes, e.g. Great Island (Horne and Patton, 1989). An estimated 0.3 x 10^6 m tons/yr of fine sediment is supplied by the river while deposition is estimated at 0.06 x 10^6 m tons/yr or about 20% of the river input (Benninger, 1976). It is likely submergence, which ranges 1.2 to 1.8 mm/yr short-term or 1.8 mm/yr long-term (Emery and Aubrey, 1991), exceeds sedimentation. But the river mouth is not an effective trap because of the high flushing velocity of river floods which pushes the salt wedge through the mouth.

The bottom sediments are dominantly sand (Gruntmeyer, 1984). Medium to coarse sand is abundant on subtidal shoals on bars and the channel floor (Figures 5A and 5B). Mud (> 20%) is significant in coves, lateral reentrants and between entrance jetties. Large fields of subaqueous dunes and megaripples indicate bedload transport is active and their asymmetrical orientation indicates ebb dominance (Gruntmeyer, 1984). Bedload is stored most of the year and then flushed into Long Island Sound during high river discharge (Horne and Patton, 1989; Scatena, 1982).

Pollution susceptibility is lower than in most other large river estuaries of the Virginia Province due to substantial flushing ability of river floods and to moderate anthropogenic activity in the drainage basin.

Bottom Sediment Charts

The bottom sediment charts, Figures 5A and 5B, are taken from Horne and Patton (1989). They are largely based on 40 grab samples obtained along transects on an approximate orthogonal grid using a mini-ranging system (Smith, 1984). The grid lines are approximately 500 m or less apart.

The distribution of mud abundance and modal size is classified as presented by the original authors, Horne and Patton (1989). The classification displays major patterns for recognizing dominant features. Since the bed is reportedly in dynamic equilibrium with the flow, these major patterns are likely to persist. Greater detail can be obtained by mapping the original data at larger scales and smaller class intervals.

For an explanation of data in the sediment inventory summary, see text and Appendix 2.

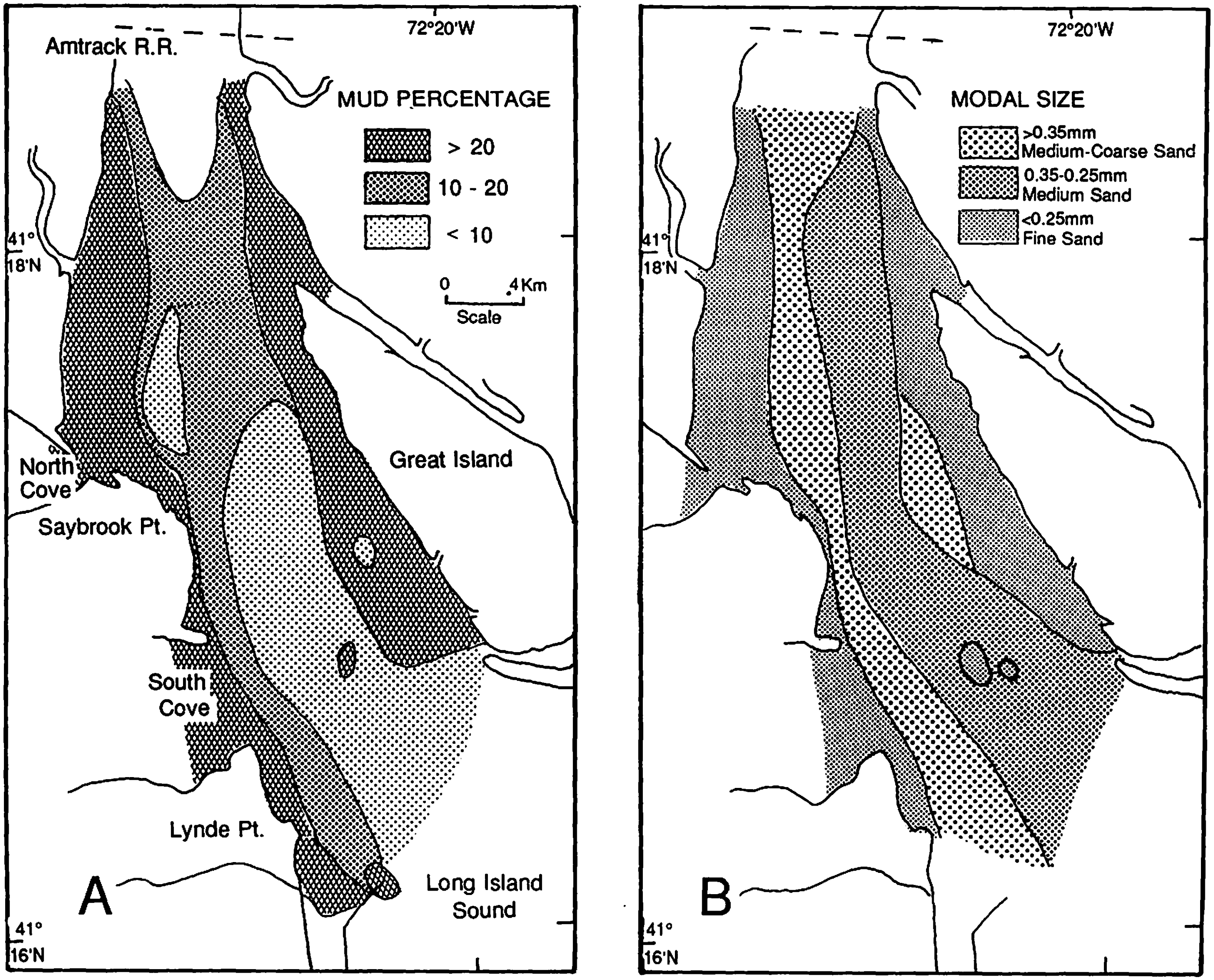


Figure 5. A. Distribution of percent mud in the lower Connecticut River from Horne and Patton (1989).
B. Distribution of modal grain size from Horne and Patton (1989).

M 040a CONNECTICUT RIVER

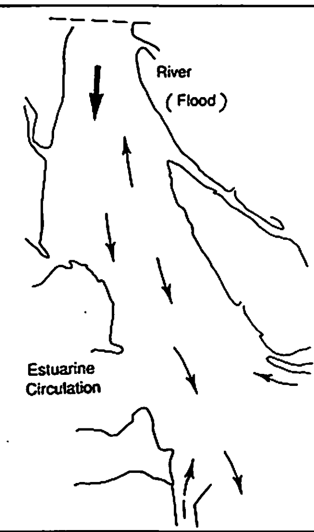
Drainage and Morphology

Total Drainage Area, Km^2	29,000
Average River Inflow, m^3/s	594
Length, Km	>100
Average Depth, m	4.0
Average Width, Km	0.9
Width/Depth Ratio	225
Surface Area, Km^2	52
Sinuosity	1.1

Sources

	Relative Strength*
Drainage Basin	High
Shores	Very Low
Marine	Low

Pathways



Submergence Rates

Short-term mm/yr	1.2-1.8
Long-term, mm/yr (0-4,000 yrs BP.)	1.8

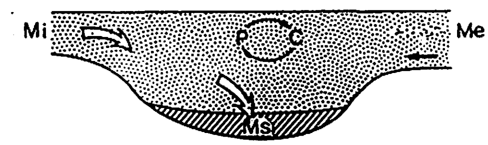
Data Quality, Bottom Sediment Texture

Fairly Certain

Sinks

	Relative Strength*
Channel	Very Low
Shoals	Low
Marshes	Low
Re-entrants, coves	High

Mass Balance



Mi + P = Ms + C + Me
(Sources) (Losses)

$0.3 = 0.06 + 0.24 \times 10^6$ tons/yr

Storage Efficiency: $Si = \frac{Ms}{\Sigma Mi} = 0.2$

Very Low

Bottom Sediment

Percent Mud Area (>20%), %	42
Percent Sand Area (>80%), %	58

Dominant Pattern:
Sand dominant; mud along shore re-entrants and coves.

Pollution Susceptibility

Relatively Low

*For total sediment

SEDIMENT CHARACTERIZATION

M060 HUDSON RIVER/RARITAN BAY

The Hudson River/Raritan Bay system is large and morphologically complex. The main compartments are: (1) tidal river, landward of Newburgh, (2) river estuary, the Narrows to Newburgh, including the Upper Bay, (3) Lower Bay/Raritan/Sandy Hook Bay seaward of The Narrows (Coch and Bokuniewicz, 1986). Numerous tidal rivers and back bays as Newark Bay, lead to a high degree of connectiveness. The drainage basin extends across six major provinces of the Appalachian Province besides a portion of the Atlantic coastal plain as well as glacial moraines and outwash plains. As a consequence, fluvial and shore source material is highly variable. Geologically the system is a drowned river valley inundated by the most recent submergence about 11,500 years ago (Weiss, 1974).

The drainage basin is the dominant fine sediment source supplying 60 to 70% of the fine-sediment input, mainly during river floods (Bokuniewicz and Ellsworth, 1986). Supply from shores is negligible because of extensive rock and bulkheaded shores. Sewage (solids) and biogenic production supply about 8% of the fine sediment while 20 to 30% comes from marine areas (Bokuniewicz and Ellsworth, 1986). Additionally, about 3% of the total input is introduced as inorganic sewage and industrial wastes (Ellsworth, 1986).

River-borne fine sediment from the mainstem and the tributaries is cycled by the estuarine circulation: i.e. (1) seaward through freshwater river reaches; (2) seaward through the upper estuarine layer and downward by settling; (3) landward through the lower estuarine layer to the inner salt limit (Newburgh). Additionally, input from marine areas is transported landward via the lower layer (Panuzio, 1963; Olsen, 1984). Large exchanges of suspended sediment can occur among different subsystems. Dredging and disposal activities are the chief processes for transport of fine sediment from the system to marine areas (Gross, 1972; Olsen *et al.*, 1984).

Sand is carried into the lower and upper bays partly from the east via longshore transport and partly from relic glacial outwash deposits on the lower bay, or inner shelf, floor. Marine sands may move landward at least to the George Washington Bridge (Coch, 1986). Alternately, fluvial sand moves seaward via the main river from Hudson to Kingston and is also supplied from lateral tributaries landward of Highlands Gorge (Coch, 1986).

Mud sedimentation is fastest (40 to 700 mm/yr) averaging about 90 mm/yr in the dredged channel between Wechawkan and Edgewater (Olsen *et al.*, 1984). Additionally, sedimentation rates are substantial (50 - 100 mm/yr) averaging 30 mm/yr in non-dredged channels between The Battery and the George Washington Bridge (Olsen *et al.*, 1984). This zone is close to the inner salt limit during extreme river floods. Between the bridge and Beacon sedimentation rates are 1 to 2 mm/yr in the channel, 1 to 5 mm/yr on shoals and 10 to 30 mm/yr in marginal reentrants. About 66% of the total sediment accumulation comes from dredged areas whereas 33% is from non-dredged areas (Olsen *et al.*, 1984; Olsen *et al.*, 1985). Mass balances indicate the Hudson stores most of the fluvial input plus sediment from other sources, marine, production and sewage. Consequently, the storage efficiency is substantial, 1.3 to 1.6.

Silty clay and clayey silt is abundant in the inner estuary, i.e. between Esopus and NJ - NY state ling (Figures 6A, 6B, 6C). Farther landward and seaward the sediments progressively coarsen (Coch, 1986). This broad tripartite pattern, sand-mud-sand, partly reflects the energy regime, i.e. strong-weak-strong, i.e. river flooding, weak tides and storm waves or strong tides. It also reflects available coarse source material at ends of the system.

A marked lateral change occurs between The Battery and Tappan Zee whereby clayey silt on the west side passes into mixed sandy or gravelly sediment in the east side (Figure 6C). This change reflects deposition from two transport routes, landward on the east and seaward on west (Coch, 1986). Thus, fine sediment from marine and fluvial areas is segregated from coarse sediment by the estuarine circulation.

In the upper bay clayey silt is deposited in a less energetic zone on the west side (NJ) whereas on the east side and in the central portion fine sediment is removed, or deposited elsewhere because of strong tidal currents (Coch, 1986). Thus, the bed is covered with sand or gravelly sand besides anthropogenic wastes. The northern lower bay is covered with sand and gravelly sand patches (Figure 6C) as a result of the underlying glacial outwash material and the energetic wave regime (Kastens *et al.*, 1978; Jones *et al.*, 1979). A broad zone of silty sand extending west of Sandy Hook, which is contaminant-rich, results from less energetic wave conditions provided by Sandy Hook and by deep water. Multer *et al.*, 1984, record silt and clay in this zone, a type that prevails in western Raritan Bay and in the Raritan River its likely source.

Newark Bay is a subsystem with coarse-grained sediment (silty sand) at ends of the system and fine-grained sediment (clayey silt) in central portions (Suszkowski, 1978). This is a tripartite pattern, reflecting proximity to the river source at the north end and strong tidal currents at the south end.

The Hudson/Raritan system supports a major shipping, industrial, railroad complex which is one of the world's busiest seaports. The high population, about 15 million people, and intense industrialization, produce enormous waste loads of water and dredged material (Gross, 1972; Duedall *et al.*, 1979).

In terms of pollution susceptibility the Hudson/Raritan system ranks high because of low flushing ability and the dense human population, including much chemical and metal activity in the drainage basin, relative to estuary surface area (Biggs *et al.*, 1989).

Bottom Sediment Charts

The bottom sediments throughout the Hudson River, Upper Bay and The Narrows are mapped by Coch (1986) from a collection of 717 grab samples. Additionally, Newark Bay was mapped from 101 grab samples (Suszkowski, 1978) and the Lower Bay/Raritan section from 159 grab samples (Kastens *et al.*, 1978) plus 35 grab samples (Jones *et al.*, 1979) and 206 grab samples (Joseph, 1983). The samples of Coch (1986) were collected from two to six stations along east-west transects about 1 km apart. Positioning techniques are not reported by Coch (1986). Grain size analyses were performed by either sieve and hydrophotometer techniques (Coch, 1986) or by sieve and pipette (Suszkowski, 1978; Kastens, 1978; Jones, 1979; Joseph, 1983).

The distribution of textural types (Figures 6A, 6B, 6C) was originally classified by a unique facies classification developed by Coch (1986). It is therefore difficult to compare mapping units and sediment distributions with other systems that are usually based on the Shepard classification. Moreover the original data are not available to remap the textural types following a standard classification. In the chartlets (Figures 6A, 6B, 6C) the classes of Coch (1986) were simplified by dropping the first textural name of a three-part name. The resulting distributions depict only boundaries of the main textural types, clay, silt and sand. It was compiled using a minimum mappable unit of 0.25 km^2 and smoothing boundaries. Narrow transition zones and small isolated patches are not shown. Greater detail can be obtained from the original chartlets (Coch, 1986).

For an explanation of data in the sediment inventory summary, see text and Appendix 2.

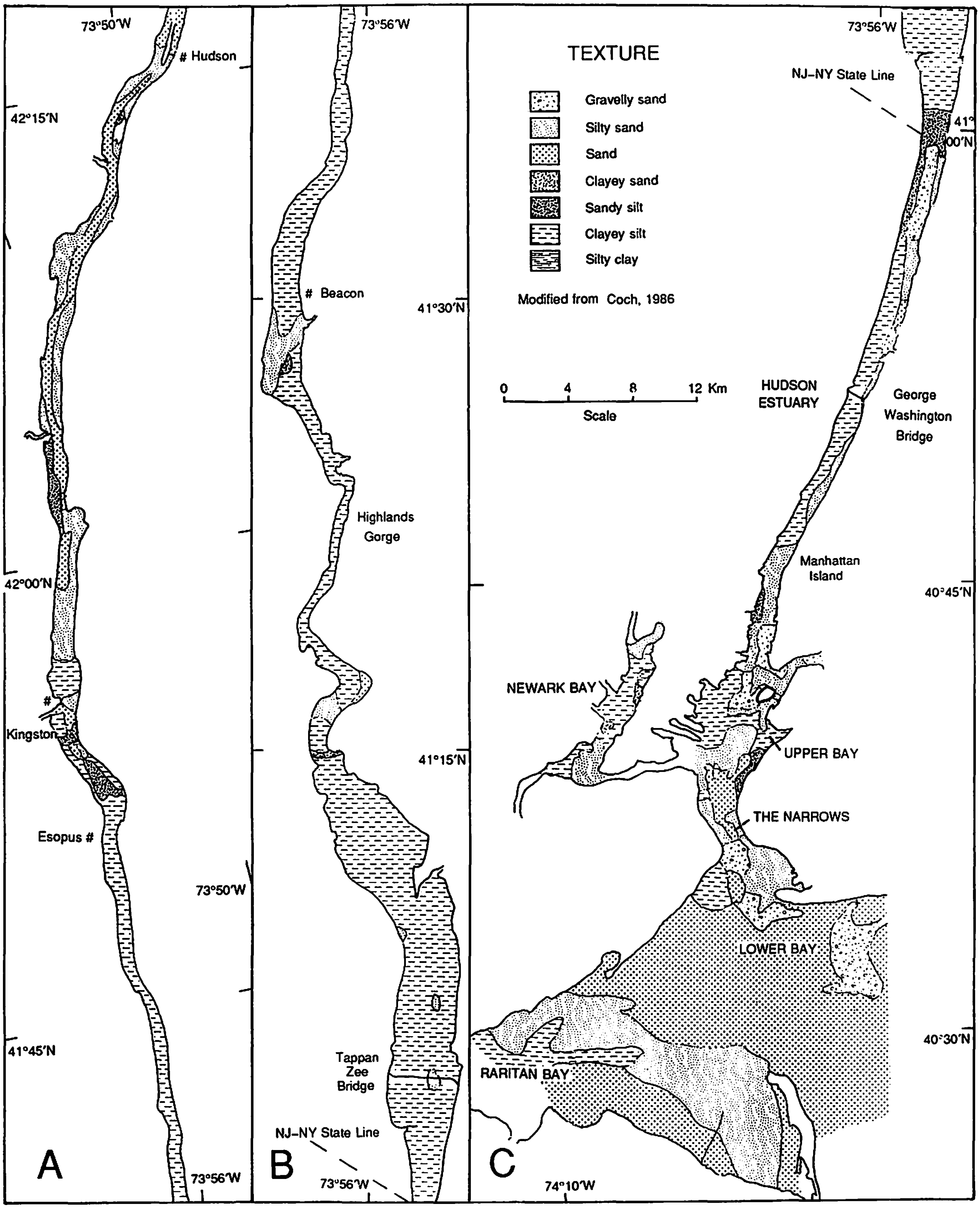


Figure 6A, B, C. Distribution of bottom sediment textural types in the Hudson River/Raritan Bay system compiled from various data sources and modified from Coch (1986).

SEDIMENT INVENTORY

M 060 HUDSON RIVER/RARITAN BAY

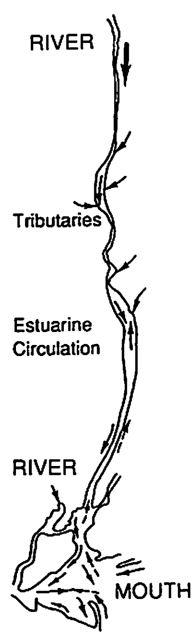
Drainage and Morphology

Total Drainage Area, Km^2	42,735
Average River Inflow, m^3/s	756
Length, Km	256
Average Depth, m	6.4
Average Width, Km	2.7
Width/Depth Ratio	422
Surface Area, Km^2	722
Sinuosity	1.1

Sources

	Tons/yr x 10^6	Strength,%*
Drainage Basin	1-1.1	60-70
Marine	.3-.5	20-30
Wastes, Inorganic	0.05	3
Production & Sewage	0.13	8

Pathways



Submergence Rates

Short-term mm/yr	0.7-3.1
Long-term, mm/yr (0-4,000 yrs BP.)	1.84

Data Quality, Bottom Sediment Texture

Moderately Certain

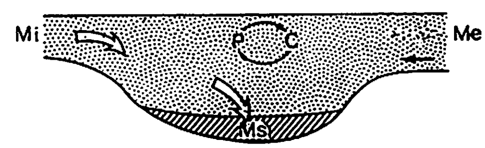
* For fine sediment

Sinks

	Tons/yr x 10^6	Strength,%*
Dredged Channels	1.0	66
Non-dredged Channels	0.5	33
Marshes	<.02	<1
Re-entrants	<.04	<3

Sedimentation Rate, mm/yr		Avg.
Dredged Channels	40-700	90
Non-dredged Channels	50-100	30
Re-entrants	10-30	

Mass Balance



Mi + P = Ms + C + Me
(Sources) (Losses)

$1.6 \pm 0.5 = 1.5 \pm 0.5 \times 10^6$ tons/yr

Storage Efficiency: $Si = \frac{Ms}{\Sigma Mi} = 1.3$ to 1.6

Bottom Sediment

Organic Matter, Av. %	6.5
Percent Mud Area**	49
Percent Sand Area**	51

Dominant Pattern:
Longitudinal: Channel, sand at head, mud middle, sand with gravel patches at Manhattan Island and seaward; tripartite pattern.
Lateral: Highly variable; in Manhattan Island reach, mud west side, sand with gravel east side.

**Based on Coch '86 classification

Pollution Susceptibility

High due to low flushing ability and high anthropogenic activity.

SEDIMENT CHARACTERIZATION

M060a RARITAN BAY

Raritan Bay receives a wide variety of contaminants from domestic sewage, industrial discharges and agriculture runoff in the drainage basin. Additionally, the bay is used for sand and gravel mining, for fisheries and recreation and it is part of one of the world's great seaports, New York (Duedall *et al.*, 1979; McCormick *et al.*, 1984). A network of dredged channels is cut through the bay at 9 to 11 m depths.

Mud is supplied mainly from the drainage basin via the Raritan River and from the Hudson River and upper bay via the upper estuarine layer (Multer *et al.*, 1984; Renwick and Ashley, 1984). A portion of the mud is deposited in the bay but another portion is transported to sea. Supply from shore erosion comes mainly from Staten Island and secondarily from northern New Jersey but the bulk of shore input is likely sand (Multer *et al.*, 1984). Sewage (solids) and production contribute about 13 to 20% of the total fine sediment input while 8 to > 20% of the total comes from marine areas via the lower estuarine layer (Olsen *et al.*, 1984). Relatively large amounts of sand are supplied to Sandy Hook and vicinity via longshore drift. Fine bed sediments undergo resuspension by storm waves and by shipping activity (Multer *et al.*, 1984). Additionally, strong winds create perturbations in the normal tidal and non-tidal currents.

The main sink of mud sedimentation is at the bay head off the Raritan River mouth (Multer *et al.*, 1984). Deposition is encouraged by protection from westerly winds, by diminished tidal currents, by inputs from major sewage outfalls and by the confluence of littoral drift. Another mud sink is Sandy Hook Bay, an area protected from ocean waves and tidal currents that receives fine sediment from the Navesink River and from wastewater discharge (Multer *et al.*, 1984). About 75% of the total deposited fine sediment accumulates in dredged areas including borrow pits, where sedimentation is about 50 to 220 mm/yr, while 25% resides in non-dredged areas (Olsen *et al.*, 1984). Mass balances indicate a range of storage efficiency for the estuary, 0.7 to 1.7 (Olsen *et al.*, 1984).

Mud (> 80%) is abundant near the bay head, but also occurs in patches through the central bay and in Sandy Hook Bay (Figure 7). The patches > 80% reside within a broad belt delineated by 40 to 80% mud isopleths. Mud is also abundant at creek mouths and in borrow pits (Figure 7). Sand (> 60%) covers areas north of the New Jersey shore, south of Staten Island and west of Sandy Hook. Where sand passes into mud there is a sharp transition of mixed sediment (40 - 60% mud) that is subject to textural change caused by storm resuspension, bed transport or human activity.

Pollution susceptibility is high because of low flushing ability and high anthropogenic activity in the drainage basin relative to estuary surface area (Biggs *et al.*, 1989).

Bottom Sediment Chart

The bottom sediments of the Raritan Bay have been mapped by Kastens *et al.* (1978) from 48 stations throughout the estuary and by Joseph (1983) from 206 stations in the southern (NJ) section and by Multer *et al.* (1984) from 80 stations estuary-wide four times a year in 1980 to 1981. The distribution of mud percentage (Figure 7) is based on bottom grabs of Kastens *et al.* (1978) and Joseph (1983). Stations of Kastens *et al.* (1978) were positioned by sextant angles on landmarks and buoys supplemented by radar ranging. The grabs recovered the top 10 to 15 cm of bottom sediment and the samples were analyzed by wet sieving. Positioning by Joseph (1983) is not reported. Data of Multer *et al.* (1984) show the seasonal persistence of sediment patterns in terms of median diameter.

The distribution of mud abundance (Figure 7) is classified into three groups and mapped by computer using a minimum mappable unit of 0.25 km^2. Narrow transition zones and small isolated patches are not shown. Greater detail can be obtained by mapping the original data at larger scales and smaller class intervals.

For an explanation of data in the sediment inventory summary, see text and Appendix 2.

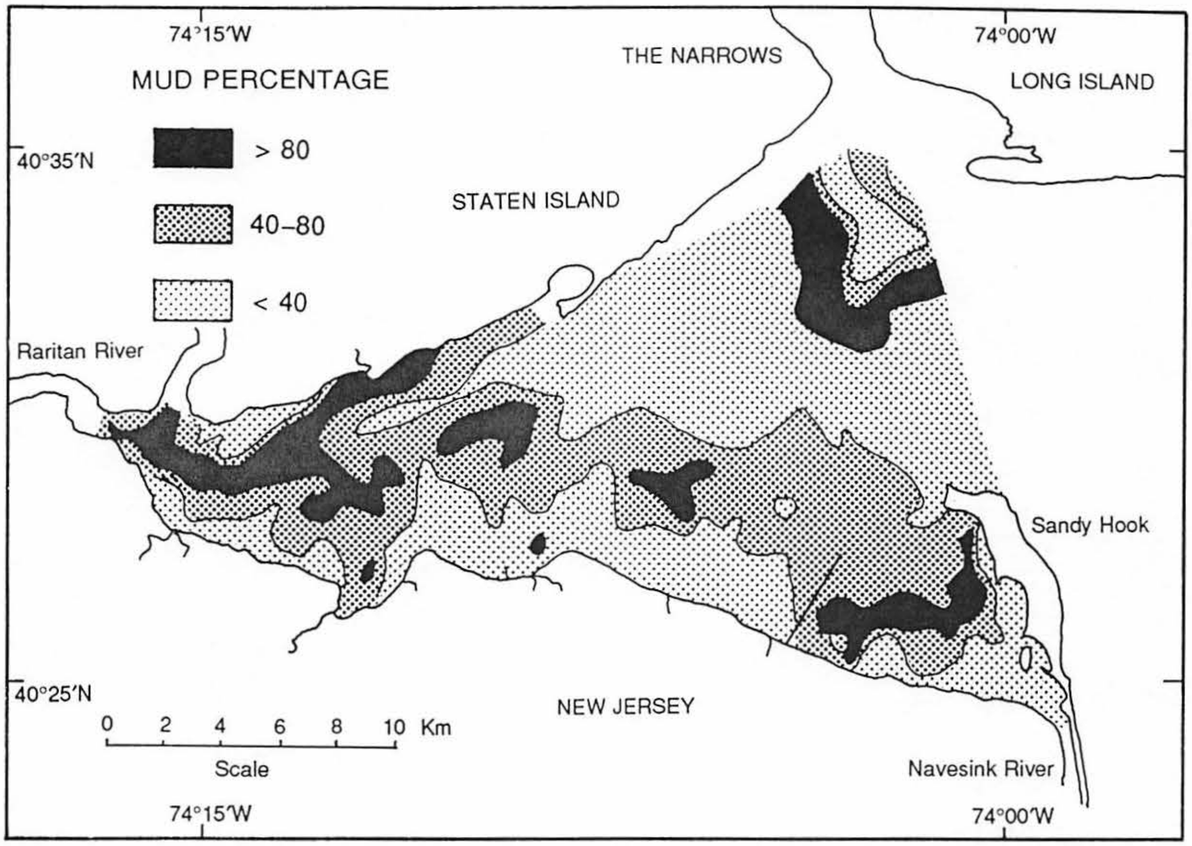


Figure 7. Distribution of mud percentage in Raritan Bay based on data of Kastens *et al.* (1978) and Joseph (1983).

SEDIMENT INVENTORY

M 060a RARITAN ESTUARY

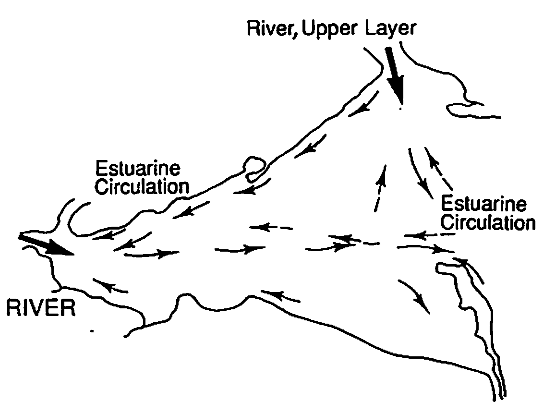
Drainage and Morphology

Total Drainage Area, Km^2	2,900
Average River Inflow, m^3/s	45
Length, Km	28
Average Depth, m	4.6
Average Width, Km	10
Width/Depth Ratio	2,174
Surface Area, Km^2	197

Sources

	Relative* Strength
Drainage Basin	Moderate
Shores	Low
Marine	Moderate
Production & Sewage	Low

Pathways



Submergence Rates

Short-term mm/yr	4.1
Long-term, mm/yr (0-4,000 yrs BP.)	1.84

Sinks

	Relative * Strength
Dredged Channels	Moderate
Non-dredged Area	Low
Borrow Pits	Low

Sedimentation Rate, mm/yr	
Dredged Channels, av.	50
Non-dredged Areas, av.	15
Borrow Pits	220

Bottom Sediment

Organic Matter, Av. %	3.0
Percent Mud Area (>40%)	78
Percent Sand Area (>60%)	22

Dominant Pattern:

Mud near river; Sandy Hook Bay and deep channel parts; sand on shoals and near mouth.

Pollution Susceptibility

High due to low flushing ability and high anthropogenic activity in the drainage basin.

Data Quality, Bottom Sediment Texture

Highly Certain

*For fine sediment

SEDIMENT CHARACTERIZATION

M090 DELAWARE ESTUARY

The Delaware Estuary contains a major shipping and industrial complex which includes the third largest seaport in the United States. Its watershed houses 7.1 million people; together with industrial plants, they produce enormous waste loads of water (Bopp, 1980) and much dredged material (Neiheisel, 1973).

The Estuary's broad funnel configuration and its axial channel are initially shaped by fluvial erosion at lower sea level. Subsequent rise of sea level in the last 8,000 years drowned the fluvial topography, eroded the shore and enlarged the estuary (Biggs, 1985). Submergence is continuing today at about 2.0 to 3.2 mm/yr being greater toward the mouth (Emery and Aubrey, 1991; Kraft *et al.*, 1987). A major dredged channel cuts through shoals 7.6 to 12 m deep in middle and upper reaches, 80 to 200 km landward of the mouth. Formerly much material was disposed in open water along channel margins but in about 1970 material was placed in diked areas on islands and along shores (Neiheisel, 1973). This practice decreased maintenance dredging about 2.5 times.

The main source of fine sediment input is the drainage basin via the river which supplies 25 to 33% of total input, mainly during floods (Neiheisel, 1973). Erosion of marshes, shores and the nearshore bottom supplies 26 to 28% of the total input. However, this is partly fine material derived from reworking of the estuary bed and recycled channelward. Mean marsh erosion amounts to 3.2 mm/yr (Weil, 1977). Additionally, some fine sediments are supplied by sewage and industrial discharges (~ 5 to 15%), from organic production of diatoms (10 to 19%) stimulated by sewage-derived nutrients, and from marine areas (~ 14%) (Neiheisel, 1973).

Fine sediment experiences repeated tidal and wave resuspension prior to accumulation. A portion is transported from open water into marshes (Strom, 1972) or alternately exported to the ocean (Oostdam, 1977). The river-borne suspended material partly follows the estuarine circulation: (1) seaward through freshwater reaches; (2) seaward through the upper estuarine layer and downward by settling; (3) landward through the lower layer to the inner salt limit, the turbidity maximum zone (Mellor, 1985).

At the mouth net seaward transport of suspended material exceeds landward transport (Oostdam, 1977). Coarse-grained bedload is partly derived from the nearshore continental shelf and the shore zone of New Jersey and transported landward around Cape May via longshore current and net density currents (Weil, 1977). This material builds arcuate shoals southwest of Cape May. Another part derived from the inner shelf, is transported through the central channel via net density currents. This material builds long linear sand ridges 1.5 to 6.0 m high along channels through the lower and middle estuary (Weil, 1977). These features are covered with numerous megaripples and sand waves 0.3 to 1.0 m high indicating a mobile bed.

The main sink of mud sedimentation is in the main shipping channel of the turbidity maximum zone, 91 to 140 km landward of the mouth, i.e. between the C&D Canal and Philadelphia (Neiheisel, 1973; Jordan, 1968). A secondary sink occurs at 189 to 206 km landward. Accumulation reaches 27 mm/yr and averages 6.8 mm/yr. This contrasts to a rate of 1.8 mm/yr in the lower bay which is the main sink of sand (Weil, 1977). Since total accumulation ranges 3.6 to 6.8 x 10^6 m tons/yr, the storage efficiency ranges 2.1 to 4.0 assuming an average river input of 1.7 x 10^6 m tons/yr.

Patches of mud (> 80%) occur in the main channel 90 to 140 km landward of the mouth (Figure 8A). Additionally, patches occur farther seaward to 38 km landward along the west side, behind the Capes and in sub-tidal shoals and bordering marshes (Weil, 1977; Strom, 1972). In the central and lower estuary, sediments become coarser-grained with depth. Coarse to medium sand occurs on the channel floor while fine to very fine sand occurs in the linear shoals. This pattern reflects vigorous tidal action in the channel and redistribution of fine material, together with reworked material, landward in less energetic zones (Weil, 1977). The overall longitudinal distribution exhibits a tripartite distribution, sand-mud-sand, following the energy regime from the mouth to Trenton and the dual input of sand from marine and fluvial areas either today or in the recent past.

Pollution susceptibility is high because of low flushing ability and the high population of chemical and metal activity (workers) relative to estuary area (Biggs *et al.*, 1985).

Bottom Sediment Chart

The bottom sediments of Delaware Bay were sampled from 411 bottom grabs and 50 piston cores by Weil (1977). Stations are distributed from the mouth landward 70 km. Farther landward to Trenton sediments were sampled at 140 stations by Neiheisel (1973) using a harpoon and shipex sampler. The samples of Weil (1977) were analyzed by sieve and pipette while those of Neiheisel (1973) were analyzed by sieve and hydrometer using a 74 μ sieve to separate fine sand and silt. Positioning methods are not reported.

The distribution of mud abundance (Figure 8A) is classified into three classes and mapped by computer. This classification displays major patterns for recognizing dominant features. This chartlet together with textural types classified by the Shepard triangle (Shepard, 1954) (Figure 8B) was compiled using a minimum mappable unit of 1.0 km^2 and smoothing isolines. Narrow transition zones and small isolated patches are not shown. Greater detail can be obtained by mapping the original data at larger scales and smaller class intervals.

For an explanation of data in the sediment inventory summary, see text and Appendix 2.

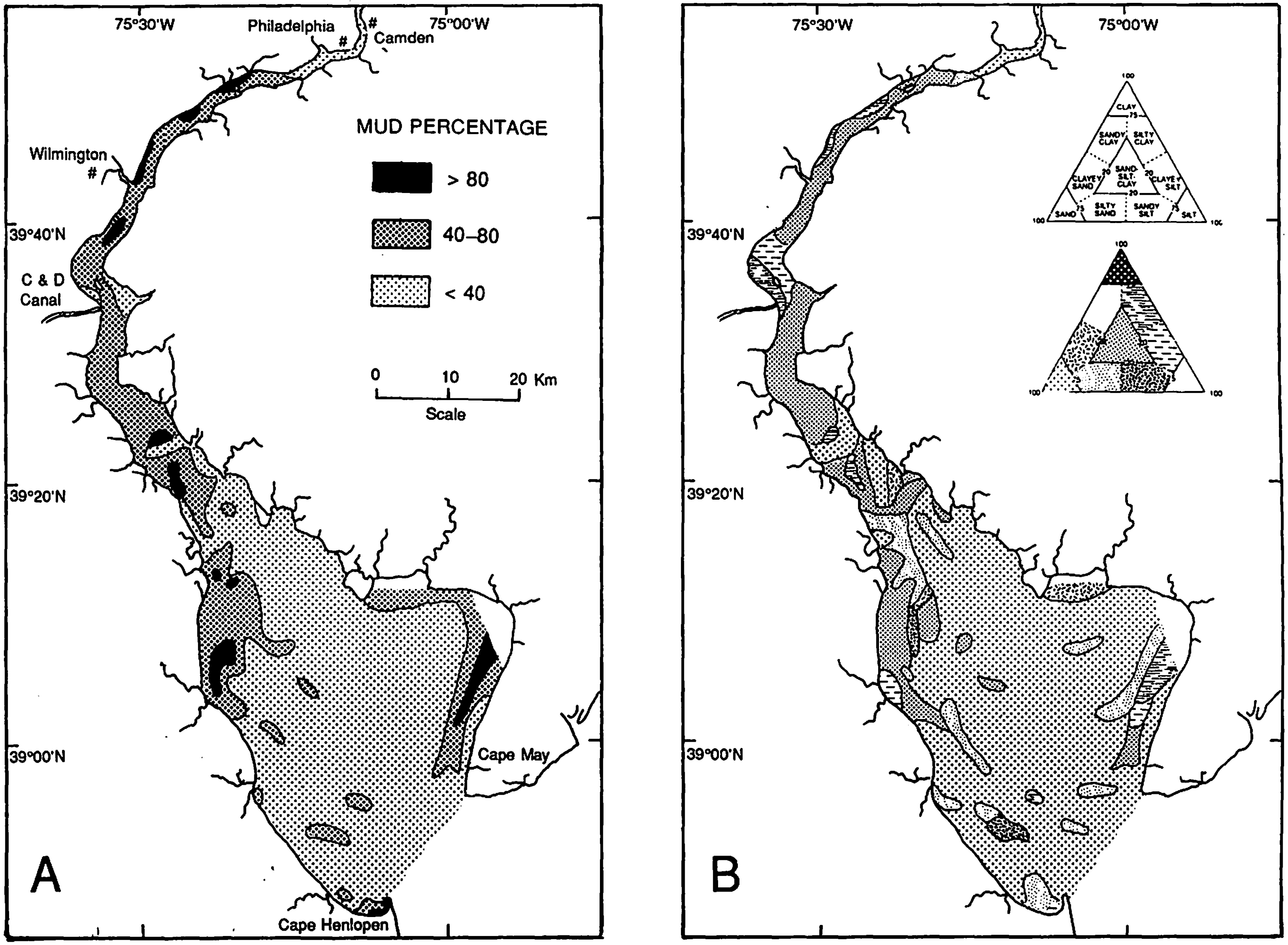


Figure 8. A. Distribution of mud percentage in Delaware Bay.
B. Distribution of sediment texture following the Shepard classification.

M 090 DELAWARE BAY

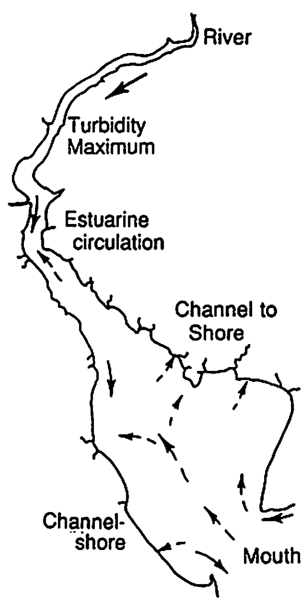
Drainage and Morphology

Total Drainage Area, Km^2	350
Average River Inflow, m^3/s	560
Length, Km	221
Average Depth, m	6.4
Average Width, Km	24
Width/Depth Ratio	3750
Surface Area, Km^2	2,036
Sinuosity	1.5

Sources

	Tons/yr x 10^6	Strength,%*
Drainage Basin	1-1.4	25-33
Shores & Marshes	1.1-1.2	26-28
Marine	0.6	14
Production	0.4-0.8	10-19
Sewage, Industrial	0.2-0.6	5-15

Pathways



Submergence Rates

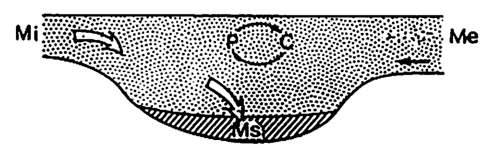
Short-term mm/yr	2.2-3.1
Long-term, mm/yr (0-4,000 yrs BP.)	2.0

Sinks

	Relative Strength*
Natural Channel	Low
Shipping Channel	High
Marsh, Creeks	Moderate

Sediment Rate, mm/yr	
Dredged Channel	>27
Mid-Upper Channel, Avg	6.8
Lower Estuary	1.8

Mass Balance



$$Mi + P = Ms + C + Me$$

(Sources) (Losses)

$4.2 = 3.6 + 0.6 \times 10^6$ tons/yr

$8.0 = 6.8 + 1.2 \times 10^6$ tons/yr

Storage Efficiency: $SI = \frac{Ms}{\Sigma Mi} = 2.1 \text{ to } 4.0$

Bottom Sediment

Percent Mud Area (>40%), %	32
Percent Sand Area (>60%), %	68
Organic Matter, Av. %	32

Dominant Pattern:

Longitude: Channel, sand at head, mud middle, sand mouth; tripartite pattern.

Lateral: Lower estuary, channel sand flanked by mud along shore.

Pollution Susceptibility

High due to low flushing ability and high anthropogenic chemical and metal activity.

Data Quality, Bottom Sediment Texture

Moderately Certain

* For fine sediment

COMPARISON OF ESTUARIES

Comparison of the seven systems selected for study highlights differences and similarities in their sediment character and potential contaminant status. Of note, fluvial input of fine sediment is the strongest term in the Delaware where about 1.1 to 2.6 x 10^6 m tons/yr is delivered. When compared to other sediment inputs within each system the Connecticut River has the most dominant fluvial input and the Hudson/Raritan a substantial input, 60 to 70% of the total input. Shore-derived material is more important in the Delaware making up 26 to 28% of the total input. All systems have a substantial input from marine areas except for the Connecticut River which is fluvial dominated. The marine input is likely transported by landward estuarine flow near the bottom and by tidal transport processes. Of note the input from marine areas into eastern Long Island Sound makes up an estimated 45% of the total input.

Depocenters of fast mud sedimentation are located in shipping channels of four systems, the Delaware, the Hudson River, Narragansett and Raritan Bay. In contrast, broad sounds with low fluvial input like Long Island Sound and Buzzards Bay have mud depocenters in deep central basins.

Storage efficiency is moderately high in Long Island Sound (2.6 to 3.6) because the fluvial input term is small and sediment accumulation rates are relatively moderate. It is moderately high in the Delaware (2.6 to 6.8) because the accumulation rate term is also moderately high despite the substantial fluvial input. These systems, in addition to Buzzards Bay and Narragansett, all have intermediate hydraulic loading values (Biggs *et al.*, 1989) that favor partial sediment trapping. In contrast, the Connecticut River has a low storage efficiency because high fluvial discharge during floods allows escape of fine sediment.

All the systems have a relatively high pollution susceptibility in terms of hydraulic loading. This means they have a large accommodative capacity to retain pollutants which is attributed to low flushing ability. Systems with substantial anthropogenic activity in watersheds, e.g. the Hudson River and Raritan Bay, are particularly susceptible to adverse effects because of the relatively high chemical and metal activity per estuarine surface area (Biggs *et al.*, 1989).

GENERALITIES

Although estuaries are typically variable and each estuary has characteristics that differ from all others, the sediment processes are similar in kind throughout most systems. Therefore, it is possible to formulate generalities, which apply to most systems in the region. They not only serve as a norm for recognizing unexpected deviations but provide a first-order guide to predicting the fate of contaminated sediments in lesser known similar systems.

1. The estuaries are submergent. As a consequence they are generally net sediment sinks and storage efficiency of fine sediment is high. The estuaries are unfilled with sediment (except the Connecticut River) and thus have a capacity to assimilate sediment in the axial channel.

2. Submergence leads to shore erosion. Shores supply a portionately large amount of material in coastal plain systems as the Delaware.

3. In systems with a strong shore supply, fine sediment is released by erosion of shores, marshes or bluffs, and secondarily by winnowing and resuspension of fines from marginal shoals. It is dispersed either channelward or basinward, alternately it is transported farther landward into marshes and creeks. Wind drift, tidal or secondary currents are the chief transport agents.

4. Estuarine sediments are mixtures derived from multiple sources including rivers, shores and marine areas. The dominance of a particular source depends on the supply rates and the exclusion of other sources.

5. Fluvial fine sediment is dispersed by the estuarine circulation following three routes: (a) seaward through freshwater reaches, (b) seaward through the upper estuarine layer and downward by settling, (c) landward through the lower layer.

6. Fine sediment, mud and organic matter which generally bear most contaminants, accumulate in less energetic zones, i.e. the shipping channels of middle or upper reaches, central basins and locally in protected reentrants, tributary creek mouths and marshes where sedimentation is fast. Prior to accumulation fine sediment goes through many cycles of settling, deposition and resuspension. This allows a long particle residence time in the water column and resultant particle-chemical interactions.

7. Accumulation and storage in the channels or basins is encouraged by low flushing ability of the systems and by particle settling and entrapment processes like the estuarine circulation. Since the salt intrusion is retained within the estuaries at all stages of river inflow, direct by-passing of fluvial material to the ocean is limited except in the Connecticut River.

8. The ultimate fate of contaminated sediment is burial in sinks where movement is negligible and concentrations are diminished by vertical mixing with less contaminated sediment, e.g. through bioturbation.

ACKNOWLEDGEMENTS

This report has benefitted from many individuals who assisted in finding data sources or contributed reference materials. Others provided valuable comments regarding interpretation of processes and quality of the data.

Buzzards Bay:

Dr. K.O. Emery, Woods Hole Oceanographic Institution, Woods Hole, MA
Dr. Frank Manheim, U.S. Geological Survey, Woods Hole, MA
Dr. John Hathaway, U.S. Geological Survey, Woods Hole, MA

Narragansett Bay:

Dr. Robert McMaster, University of Rhode Island, Graduate School of Oceanography, Kingston, RI
Dr. Jeff Corbin, U.S. Environmental Protection Agency, Narragansett Laboratory, Kingston, RI
Dr. John King, University of Rhode Island, Graduate School of Oceanography, Kingston, RI

Connecticut River:

Dr. G.S. Horne, Department of Geology, Wesleyan University, Middletown, CT

Long Island Sound:

Dr. Henry Bokuniewicz, Marine Sciences Research Center, State University of New York, Stony Brook, NY
Dr. Frank Bohlen, Marine Sciences Institute, University of Connecticut, Groton, CT
Dr. Daniel Farrow, NOAA/SEA Division, Rockville, MD
Dr. Robert Reid, NOAA, National Marine Fisheries Service, Sandy Hook Laboratory, Highlands, NJ

Hudson River:

Dr. Dominichi D. Toro, Manhattan College, Riverdale, NY
Dr. Dennis Suszkowski, Hudson River Foundation, New York City, NY
Dr. Nicholas Coch, Department of Geology, Queens College, NY

Raritan Bay:

Mr. James Joseph, NJ Department of Environmental Protection, Division of Fish, Game and Wildlife, Nacote Creek Research Station, NJ
Dr. Gail Ashley, Department of Geological Sciences, Rutgers University, New Brunswick, NJ
Dr. Gray Multer, Dickinson University, Madison, NJ
Dr. M.J. Hall, Ryder College, Lawenceville, NJ
Dr. Sue Halsey, NJ Department of Environmental Protection, Ft. Hancock, NJ

Delaware Bay:

Dr. Ronald Gibbs, College of Marine Studies, University of Delaware, Newark, DE
Dr. John Sharp, College of Marine Studies, University of Delaware, Newark, DE
Mr. Eric Stern, U.S. Environmental Protection Agency, Region 2, New York, NY
Ms. Barbara Conlin, U.S. Army Corps of Engineers, Philadelphia District, Philadelphia, PA
Mr. James McNair, Academy of Natural Sciences, Philadelphia, PA
Mr. Steve Friant, Academy of Natural Sciences, Philadelphia, PA

REFERENCES

Bader, R.G., 1954. Use of factors for converting carbon or nitrogen to total sedimentary organics. *Science* 120:709-710.

Bader, R.G., 1955. Carbon and nitrogen relations in surface and subsurface marine sediments. *Geochim. et Cosmochim. Acta* 7:205-211.

Bennett, R.H. and D.N. Lambert, 1971. Rapid and reliable technique for determining unit weight and porosity of deep-sea sediments. *Mar. Geol.* 11:201-207.

Benninger, L.K., 1976. *The Uranium-Series Radionucleides as Tracers of Geochemical Processes in Long Island Sound.* Ph.D. Dissertation, Yale University, New Haven, CT.

Biggs, R.B., 1985. Geological history and setting. In: D.M. Goodrich (ed.), *Delaware Bay: Issues, Resources, Status and Management.* NOAA Estuary-of-the-Month, Sem. Ser. 2, Proc., March 1, 1985, Washington, D.C., p. 17-28.

Biggs, R.B., T.B. DeMoss, M.M. Carter, and E.L. Beasley, 1989. Susceptibility of U.S. estuaries to pollution. *Rev. Aquatic Sci.* 1:189-207.

Bokuniewicz, H.J., 1980. Sand transport at the floor of Long Island Sound. *Advances in Geophy.* 22:107-128.

Bokuniewicz, H.J. and R.B. Gordon, 1980. Sediment transport and deposition in Long Island Sound. *Advances in Geophy.* 22:69-106.

Bokuniewicz, H.J., B.H. Brinkhuis, K.N. Chytalo, G. Colvin, D. Cunningham, D.J. Fallon, R.B. Gordon, D.J. Hirschberg, J.M. Jeffrey, R. Miller, H.B. O'Connors, S.F. Robbins, P.T. Sanko, J.R. Schubel, O.W. Terry, B. Webster, P.K. Weyl, W.M. Wise, J.Y. Yingst, and C.R. Zeppie, 1979. *Questions about Dredging and Dredged Material Disposal in Long Island Sound.* J.R. Schubel, W.M. Wise and J. Schoof (eds.), Spec. Rep. 28, Ref. 79-11, 136 p.

Bokuniewicz, H.J. and J.M. Ellsworth, 1986. Sediment budget for the Hudson system. *Northeastern Geol* 8(3):141-155.

Bopp, F., III, 1980. *Trace Metal Geochemistry of Upper Delaware Bay.* Ph.D. Dissertation, University of Delaware, 378 p.

Brush, G.S., 1990. *Sedimentation Rates in the Chesapeake Bay. Final Report.* Prepared for the U.S. Environmental Protection Agency, 44 p.

Coch, N.K., 1986. Sediment characteristics and facies distributions in the Hudson System. *Northeastern Geol.* 8(3):109-129.*

* Primary data sources used for data base input and digital charting.

Coch, N.K. and H.J. Bokuniewicz, 1986. Oceanographic and geologic framework of the Hudson system. *Northeastern Geol* 8(3):96-108.

Corbin, J.M., 1989. *Recent and Historical Accumulation of Trace Metal Contaminants in the Sediments of Narragansett Bay, Rhode Island.* M.S. Thesis, University of Rhode Island, Kingston, RI, 284 p.

Duedall, I.W., H.B. O'Connors, R.E. Wilson, and J.H. Parker, 1979. *The Lower Bay Complex.* Marine EcoSystems Analysis Program, New York Bight Project, Monog. 29, New York Sea Grant Inst., 47 p.

Ellsworth, J.M., 1986. Sources and sinks for fine-grained sediment in the lower Hudson River. *Northeastern Geol.* 8(3):141-155.

Emery, K.O. and D.G. Aubrey, 1991. *Sea Levels, Land Levels and Tide Gauges.* Springer-Verlag Inc., NY, 237 p.

Farrow, D.R.G., F.D. Arnold, M.L. Lombardi, M.B. Main, and D.D. Elchelberger, 1986. *The National Coastal Pollution Discharge Inventory: Estimates for Long Island Sound.* NOAA, Rockville, MD, 40 p.

Fitzgerald, D.M., C.T. Baldwin, N.A. Ibrahim, and D.R. Sands, 1987. Development of the northwestern Buzzards Bay shoreline, Massachusetts. In: D.M. Fitzgerald and P.S. Rosen (eds.), *Glaciated Coasts*, Academic Press, San Diego, CA, p. 327-357.

Frey, R.W., J.D. Howard, and J. Dorjes, 1989. Coastal sediments and patterns of bioturbation, eastern Buzzards Bay, Massachusetts. *J. Sed. Petrol.* 59:1022-1035.

Gordon, R.B., 1980. The sedimentary system of Long Island Sound. *Advances in Geophy.* 22:1-39.

Greig, R.A. and R.A. McGrath, 1977. Trace metals in sediments of Raritan Bay. *Mar. Poll. Bull.* 8(8):188-192.

Gross, M.G., 1972. Geological aspects of waste solids and marine waste deposits in New York metropolitan region. *Geol. Soc. Am. Bull.* 83:3163-3176.

Gruntmeyer, P.A., 1984. *Bedload Sediment Transport Pathways in the Lower Connecticut River Estuary.* Unpubl. M.A. Thesis, Wesleyan University, Middletown, CT, 137 p.

Horne, G.S. and P.C. Patton, 1989. Bedload-sediment transport through the Connecticut River Estuary. *Geol. Soc. Amer. Bull.* 101:805-819.*

Hough, J.L., 1940. Sediments of Buzzards Bay, Massachusetts. *J. Sed. Petrol.* 10(1):19-32.

Jones, C.R., C.T. Fray, and J.R. Schubel, 1979. *Textural Properties of Surficial Sediments of the Lower Bay of New York Harbor.* Marine Science Research Center, SUNY, Stony Brook, NY, Spec. Rep. 21, Ref. 79-4, 113 p.*

Jordan, R.R., 1968. *Suspended and Bottom Sediments in the Delaware Estuary.* Dept. Geology, University of Delaware, Newark, DE, (Abstract).

Joseph, J.W., 1983. *Shellfish Inventory: Sandy Hook and Raritan Bays.* NJ Dept. of Environmental Protection, Div. of Fish, Game and Wildlife, Unpubl. Data, 42 p.*

Kastens, K.A., C.T. Fray, and J.R. Schubel, 1978. *Environmental Effects of Sand Mining in the Lower Bay of New York Harbor.* Marine Sciences Research Center, SUNY, Stony Brook, NY, Spec. Rep. 15, Ref. 78-3, 139 p.*

Kim, B.-H. and H.J. Bokuniewicz, 1991. Estimates of sediment fluxes in Long Island Sound. *Estuaries* 14(3):237-247.

King, J., J. Corbin, and P. Gangemi, 1992. *Trace Metal Contaminants in Surface Sediments of Narragansett Bay.* Unpubl. Cont. Rep., U.S. EPA, p. 32-77.

Koppelman, L.E., P.K. Weyl, M.G. Gross, and D.S. Davies, 1976. *The Urban Sea: Long Island Sound.* Praeger Publishers, NY, 223 p.

Kraft, J.C., M.J. Chrzastowski, D.F. Belknap, M.A. Toscano, and C.H. Fletcher, III, 1987. The transgressive barrier-lagoon coast of Delaware: Morphostratigraphy, sedimentary sequences and responses to relative rise in sea level. In: *Coast of Delaware.* Soc. Econ. Paleontol. Mineral., p. 129-143.

McCormick, J.M., H.G. Multer, and D.M. Stainken, 1984. A review of Raritan Bay research. *Bull. New Jersey Acad. Sci.* 29(2):47-58.

McMaster, R.L., 1956. *A Survey of Bottom Surface Sediments in Lower Sakonnet Bay.* (Pers. Comm., unpubl.) 3 p.*

McMaster, R.L., 1960. Sediments of Narragansett Bay system and Rhode Island Sound, Rhode Island. *J. Sed. Petrol.* 30(2):249-274.*

McMaster, R.L., 1984. Holocene stratigraphy and depositional history of the Narragansett Bay System, Rhode Island, U.S.A. *Sedimentology* 31:777-792.

McMaster, R.L. and W.B. Clarke, 1956. *A Survey of Bottom Surface Sediments in Upper Narragansett and Mt. Hope Bays.* Submitted, U.S. Army Corps of Engineers, Ref. 56-14, Rep. 1, 15 p.*

McMaster, R.L., D.E. Frazier, and R.E. Carr, 1956. *A Survey of Bottom Surface Sediments in Lower Narragansett Bay.* Submitted to U.S. Army Corps of Engineers, Ref. 56-18, Rep. 2, 12 p.*

Moore, J.R., 1963. Bottom sediment studies, Buzzards Bay, Massachusetts. *J. Sed. Petrol.* 33(3):511-558.*

Morton, R.W., 1967. *Spatial and Temporal Observations of Suspended Sediment: Narragansett Bay and Rhode Island Sound.* Tech. Mem. TM 36, Naval Underwater Weapons Res. Eng. Station, Newport, RI, 33 p.

Multer, H.G., D.M. Stainken, J.M. McCormick, and K.J. Berger, 1984. Sediments in the Raritan Bay - lower New York Bay complex. *Bull. New Jersey Acad. Sci.* 29(2):79-96.*

Neiheisel, J., 1973. *Long Range Spoil Disposal Study, Part III, Sub-Study 2: Nature, Source, and Cause of the Shoal, Appendix A.* U.S. Army Eng. Dist. Philadelphia Corps Eng., 140 p.*

Nichols, M.M., 1986. Storage efficiency of estuaries. In: S.Y. Wang and H.W. Shen (eds.), *Proc. 3rd International Symp. on River Sedimentation*, Univ. of Mississippi, p. 273-289.

Nixon, S., 1985. Overview. In: *Narragansett Bay: Issues, Resources, Status and Management.* NOAA Estuary-of-the-Month, Sem. Ser. 1, p. 7-16.

Nixon, S., C.D. Hunt, and B.L. Nowicki, 1986. The retention of nutrients (C,N,P), heavy metals (Mn, Cd, Pb, Cu), and petroleum hydrocarbons in Narragansett Bay. In: P. Lasserre and J.M. Martin (eds.), *Biogeochemical Processes at the Land-Sea Boundary*, Elsevier Oceanography Series 43, Elsevier, Amsterdam, p. 99-122.

Olsen, C.R., N.H. Cutshall, I.L. Larsen, H.J. Simpson, R.M. Trier, and R.F. Bopp, 1985. An estuarine fine-particle budget determined from radionuclide tracers. *Geo-Mar. Let.* 4:157-160.

Olsen, C.R., I.L. Larsen, R.H. Brewster, N.H. Cutshall, R.F. Bopp, and H.J. Simpson, 1984. *A Geochemical Assessment of Sedimentation and Contaminant Distributions in the Hudson-Raritan Estuary.* NOAA Tech. Rep. NOS OMS 2, 101 p.*

Oostdam, B.L., 1977. Suspended sediment transport in the Delaware Bay. In: I.H. Suffet (ed.), Fate of Pollutants in the Air and Water Environments. *Env. Sci. Tech.* 8:425-461.

Panuzio, F.L., 1965. Lower Hudson River siltation. In: *Proceedings of Federal Inter-Agency Sedimentation Conf., 1963*, Misc. Publ. No. 970, Agriculture Research Service, Jackson, MS, p. 512-550.

Reid, R.N., A.B. Frame, and A.F. Draxler, 1979. *Environmental Baselines in Long Island Sound, 1972-73.* U.S. Government Printing Office, NOAA Technical Report NMFS SSRF-78, 31 p.

Renwick, W.H. and G.M. Ashley, 1984. Sources, storages, and sinks of fine-grained sediments in a fluvial-estuarine system. *Geol. Soc. Am. Bull.* 95:1343-1348.

Rhoads, D.C., 1967. Biogenic reworking of intertidal and subtidal sediments in Barnstable Harbor and Buzzards Bay, Massachusetts. *J. Geol.* 75:461-476.

Sanders, H.L., 1958. Benthic studies in Buzzards Bay: I. Animal-sediment relationships. *Limnol. Oceanogr.* 3(3):245-258.

Santschi, P.H., S. Nixon, M. Pilson, and C. Hunt, 1984. Accumulation of sediments, trace metals (Pb, Cu) and total hydrocarbons in Narragansett Bay, Rhode Island. *Est. Coastal Shelf Sci.* 19:427-449

Scatena, F.N., 1982. *Patterns of Bedload Transport in the Connecticut River Estuary.* Unpubl. M.A. Thesis, Wesleyan University, Middletown, CT, 124 p.

Schubel, J.R., 1987. Long Island Sound in Time and Space: An Overview. In: V.R. Gibson and M.S. Connor (eds.), *Long Island Sound: Issues, Resources, Status and Management.* NOAA Estuary-of-the-Month Sem. Ser. 3, p. 1-21.

Seavey, G.L. and D.S. Pratt, 1979. *The Disposal of Dredged Material in Rhode Island: An Evaluation of Past Practices and Future Options.* University of Rhode Island Mar. Tech. Rep. 72, 46 p.

Shepard, F.P., 1953. Sedimentation rates in Texas estuaries and lagoons. *Am. Assoc. Petrol. Geol. Bull.* 37:1919-1934.

Shepard, F.P., 1954. Nomenclature based on sand-silt-clay ratios. *J. Sed. Petrol.* 24:151-158.

Smith, G.L., 1984. *Bedload Sediment Transport in the Lower Estuary of the Connecticut River.* Unpubl. B.A. Honors Thesis, Wesleyan University, Middletown, CT, 70 p.

Spaulding, M., 1985. Circulation Dynamics. In: *Narragansett Bay: Issues, Resources, Status and Management.* NOAA Estuary-of-the-Month Sem. Ser. 1, p. 71-146.

Strom, R.N., 1972. *Sediment Distribution in Southwestern Delaware Bay.* University of Delaware, College of Marine Studies, Tech. Rep. 18., 92 p.

Summerhayes, C.P., J.P. Ellis, and P. Stoffers, 1985. Estuaries as Sinks for Sediment and Industrial Waste--a Case History from the Massachusetts Coast. In: H. Fuchtbauer, A.P. Lisitzyn, J.D. Milliman, E. Seibold (eds.), *Contributions to Sedimentology*, Vol. 14, 47 p.

Suszkowski, D.J., 1978. *Sedimentology of Newark Bay, N.J.: An Urban Estuarine Bay.* Ph.D. Dissertation, University of Delaware, 222 p.*

Tanski, J.J., 1981. *Episodic Bluff Erosion on the North Shore of Long Island, New York.* MS Thesis, State University of New York, Stony Brook, NY, 82 p.

U.S. NOAA, National Oceanic and Atmospheric Administration, 1990. *Estuaries of the United States; Vital Statistics of a National Resource Base*, 79 p.

U.S. NOAA, 1985. *National Estuarine Inventory: Data Atlas, Vol. 1: Physical and Hydrologic Characteristics*. Strategic Assessment Branch, Rockville, MD, 103 p.

Weil, C.B., 1977. *Sediments, Structural Framework, and Evolution of Delaware Bay, a Transgressive Estuarine Delta*. Delaware Sea Grant College Program, University of Delaware, Ref. DEL-SG-4-77, 199 p.*

Weiss, D., 1974. Late Pleistocene stratigraphy and paleoecology of the lower Hudson River Estuary. *Geol. Soc. Am. Bull.* 85:1561-1570.

Wilson, R.E., 1987. Modeling for Management. In: V.R. Gibson and M.S. Connor (eds.), *Long Island Sound: Issues, Resources, Status and Management*. NOAA Estuary-of-the-Month Sem. Ser. 3, p. 89-95.

Appendix 1

Organization of data quality and criteria used for assessment of scientific certainty.

1. DATA SOURCE QUALITY

(1) Data Forms

Data produced by laboratory analysis of sediment texture (e.g. wet-sieving, pipetting, hydrometer and settling tube analysis, etc.) is considered the highest quality. Numeric values (e.g. tables, computer files) are considered to produce a better data set than isopleths or charted distributions. NOS bottom notations or field descriptions are considered the lowest quality.

	Weight
A. Laboratory Processed	
- Available as measured values	3
- Available as isopleths or charted distributions	2
B. Non-Laboratory Processed	
- NOS bottom notations or visual description	1

(2) Degree of Laboratory Processing

Laboratory processed data in terms of percent sand-silt-clay, which enables Shepard's classification of sediment texture, has priority over statistical parameters (e.g. mean, median, mode, sorting, etc.). The percent mud or sand/mud ratio, which is usually measured by wet sieving, is also considered to have lower quality than percent sand-silt-clay.

A. Percent Sand-Silt-Clay	2
B. Percent Mud, Mean, or Median	1

(3) Documentation

Published data which has been peer-reviewed is regarded highly certain. Semi-published "grey" literature, including technical reports, theses, or dissertations are not peer-reviewed and regarded as lesser quality.

A. Published	3
B. Semi-published "Grey" Literature, Tech. Reports, Theses, or Dissertation	2
C. Unpublished Field Data	1

(4) Spatial Sampling Density

Sampling density is determined by the number of stations per 10 Km^2. This is the most important factor affecting source data quality. The critical values of 1,3,5, and 7 are set by testing the data for the Chesapeake Bay and its tributaries.

A. > 7 stations / 10 km^2	5
B. 5 - 7 stations / 10 km^2	4
C. 3 - 5 stations / 10 km^2	3
D. 1 - 3 stations / 10 km^2	2
E. < 1 stations / 10 km^2	1

(5) Additional Parameters

The textural parameters are often interrelated to other measured parameters (e.g. organic content, water content, etc.). Whenever these additional parameters are measured and abundant, the data quality is more assured.

A. Available other parameters	1

The data source quality weightings are normalized by dividing by 15 (the maximum number of points) and the maximum weighting value is set to 100 percent.

2. MAPPABILITY

(1) Sampling Density

When several sets of source data are used to map an estuary, the sampling density in terms of the whole estuary is important to determine the mappability. The values of 3 and 7 stations/10 km^2 are set by testing the data for the Chesapeake Bay and its tributaries.

	Weight
A. > 7 stations / 10 km^2	3
B. 3 - 7 stations / 10 km^2	2
C. < 3 stations / 10 km^2	1

(2) Spatial Coverage

The end product of the computer processing is a chart which shows the distribution of values by parameter from one or several data sources. The coverage in terms of percent of the whole estuary is used to assure the certainty of data representation.

A. > 80 %	3
B. 60 - 80 %	2
C. < 60 %	1

(3) Consistency, Number and Compatibility of data sets

Variations of different data sources in time and space are important in producing consistent composite charts. The best chart consists of a single data source that covers the whole estuary at one time. The smaller the number of data sources in a composite, the better the mappability.

A. 1 - 2	3
B. 3 - 4	2
C. > 4	1

(4) Temporal Coverage

Multiple coverage of the same area at several times strengthens the reliability of a chart.

A. Over two data sets	2
B. Less than two data sets	1

(5) Additional Parameters

The distribution of additional parameters strengthens the reliability of a chart since many parameters are interrelated to grain size.

A. Other parameters available	1

The data mappability weightings are normalized by dividing by 12 (the maximum number of points) and the maximum weighting value is set to 100 percent.

3. AGGREGATE QUALITY

Normalized weightings of all data source quality values and mappability values are then averaged and assigned descriptors.

(1) > 85	Highly Certain	-	Excellent Data Set and Mappability
(2) 70 - 85	Moderately Certain	-	Good Data Set and Mappability
(3) 55 - 70	Fairly Certain	-	Fair Data Set and Fair Mappability
(4) 40 - 55	Reasonable Inference	-	Fair Data Set and Reasonable Mappability
(5) < 40	Doubtful	-	Rejected Data Set

Appendix 2

KEY TO SEDIMENT INVENTORY SHEETS

Code Number is a NOAA code to identify estuary systems included in the National Estuarine Inventory (NEI). M numbers are for systems in the Middle Atlantic region.

Drainage and Morphology give the fundamental hydrologic and morphologic data from NOAA, 1990; drainage area embraces the total drainage area including the estuarine drainage area and the fluvial drainage area; river (stream) inflow is the annual average inflow for the entire system; width is the average width; depth the average depth for the entire system; depth/width ratio is the ratio of estuary depth to width; sinuosity of river estuaries is the ratio of channel length to valley length.

Sources are the sediment sources for either: 1) the total sediment input, e.g. mud, sand and biogenic material, or 2) the total fine sediment, e.g. mud or silt plus clay. Where input rates are known such as part of a mass balance, the strength is expressed as a percentage of the whole. Where rates of input are not measured the source is reported qualitatively according to its relative strength in the system; very low is 0 - 10%; low is 11 - 30%; moderate is 31 to 70%; high is 71 to 100%.

Pathways are the likely routes of sediment transport from the source to the sink, or loss by export, displayed in plan view. Bold arrow represents relatively strong transport; thin arrow, weak transport. Near-bottom transport, dashed arrow; near-surface, solid.

Submergence Rates are the rates of relative land (sea) level change either short-term based on tide gages over periods of 20 to 80 years, or long-term, geologic trends in the last 4,000 - 7,000 years.

Sinks are sediment accumulation zones in the estuary for either: 1) total sediment, or 2) fine sediment. Where accumulation rates are known such as part of a mass balance, the strength is expressed as a percentage of the whole. Where measured rates are not available the sink is reported qualitatively according to its relative strength; very low is 0 - 10%; low is 11 - 30%; moderate is 31 to 70%; high is 71 to 100%.

Mass Balance is a sediment budget for either: 1) total sediment, or 2) fine sediment, in which the sources (inputs) are balanced by the losses, i.e. into the sinks or through export to the ocean. Data come mainly from the published literature reported in the characterization reports. Two or more balances reflect a range of estimates from different data sources and in turn, different methodology or data uncertainties.

Storage Efficiency is the ability of an estuary to retain and accumulate fine sediment delivered to it. This is expressed as a ratio of the accumulation rate in all sinks to the drainage basin input rate. The rates come from the mass balance. A ratio of one implies the amount of sediment is equivalent to the amount supplied by the drainage basin. A ratio greater than one implies the estuary stores more sediment than is supplied by its drainage basin.

Bottom Sediments

Mud Area is the percentage of the total estuary area occupied by mud > 40%. In systems lacking mud > 40%, an alternate percentage or class is substituted as indicated.

Sand Area is the percentage of the total NEI estuary (surface) area > 60% sand. In systems lacking > 60%, an alternate percentage or class is substituted as indicated.

Water Content is the mean percentage water content expressed as wet weight (0 to 100%).

Organic Matter is the mean percentage organic matter. Where original source data are expressed as organic carbon, the carbon values were multiplied by a factor of 1.8 to obtain organic matter values.

Pattern is the gross distribution of sand and mud, i.e. longitudinally along the channel from head to mouth or laterally across the middle or lower portion of the system. In some systems the dominant pattern is described according to morphologic features.

Pollution Susceptibility is the relative pollution potential of the system as determined by 1) hydraulic characteristics, i.e. ability of the system to flush dissolved pollutants, and 2) exposure to anthropogenic activities in the drainage basin. Relative rankings are from Biggs *et al.* (1989) and based on comparison of 78 U.S. estuaries. For further explanation see text.

Data Quality is the overall relative quality of textural data including the quality of the data source(s) and the mappability of combined sources. Rankings range "highly certain," "moderately certain," "fairly certain," "reasonable inference" and "doubtful." For details see Appendix 1.